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THE VARIATION OF THE ANGLE OF INTERNAL FRICTION WITH SIZE CONSIST FOR MECHANICALLY-CHIPPED MATERIAL-YEAR TWO

Lee W. Saperstein, et al

Pennsylvania State University

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Test results indicate a decrease in the angle of internal friction with an increase in individual particle size, and with the use of some saturation fluids. Results also reveal an increase in the angle of internal friction with an increase in overall size consist for noncohesive materials. (U) R

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Technical Report Summary

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CHAPTER 1

INTRODUCTION

The Problem

The continuing increase in urbanization along with justified demands for a clean and more efficiently utilized environment demonstrate the need for increased use of the subsurface. Technologies to improve this use are often grouped in the phrase "Rapid Excavation." During the last fifteen years tunneling machines, as an alternative to the traditional drill-and-shoot method of excavation, have been used increasingly to bore water tunnels, sewer lines, subways, and other transportation tunnels. Increasing use of tunneling machines, however, results in the need for related technological improvements. One major inefficient discipline in need of improvement is materials handling.

The angle of internal friction (sometimes called the friction angle, or simply ϕ) is an important independent parameter found in many materials handling equations (9, 20, 24). This materials handling parameter is actually a number analogous to the coefficient of sliding friction, which relates the shear strength of granular material to the normal force acting on it. "Angle" and "strength" are consequently often used interchangeably, i.e. a material with a high angle of internal friction has a high strength, and vice versa. It is known that this

angle varies with mineralogy, but how this angle varies with particle size and size consist is still not completely clear. Should there in fact be some variation in the angle of internal friction with changes in particle size or consist, it might be possible to improve the materials handling aspects of tunneling by machine through artificial variations in the angle of internal friction by altering particle sizes. This could possibly be accomplished through variations in bit type and configuration, machine thrust, and cutter head rpm. Variations in these parameters are discussed in greater detail in Chapters 4 and 5 of this paper.

Purpose of the Study

To date, limited research has been conducted to determine variations in the angle of internal friction with changes in particle size. Some of this previous work is summarized in Chapter 2 of this paper. Due to differences in testing techniques and materials tested, there still exists some disagreement as to how ϕ varies with changes in particle size.

Until now the materials tested for changes in ϕ have come from rock quarries, laboratory crushers, etc. No known work has been done on materials actually produced by tunneling machines. The purpose of this study is, therefore, to examine the variations in the angle of

internal friction with changes in particle size for mechanically-chipped material, that is muck produced by tunneling machines. This is accomplished by collecting muck samples from several tunnel sites, and then testing the various size fractions and consists in triaxial cells in order to determine ϕ. Variations in the angle of internal friction for individual size fractions as well as the variations with changes in overall size consist are studied. Throughout this report the terms "uniformly graded" and "well graded" are used. Uniformly graded refers to a sample of uniform or nearly uniform size consist, e.g. all 40 mesh material. Well graded refers to a sample containing the entire spectrum of particle sizes from minus 270 mesh to two inch.

Most tunneling machines use water sprays at the face to suppress dust, and to cool and lubricate bits. Alternative fluids for spraying are being studied by others (18, 19, 22, 28, 29) for the purpose of improving dust suppression in one case, and for improving drillability in another case. As a tangential study, two of these fluids (a dust suppressor and a rock softener) are used in place of pure water as the saturation fluid in the triaxial test. The purpose is, of course, to determine what effect, if any, a change in spray fluid on the tunneling machine might have on the angle of internal friction.

In addition to field related studies it is intended also to check size effects in laboratory equipment. For efficient muck utilization and maintenance it is necessary to use more than one cell size in laboratory testing.

Scope

Since this investigation is concerned with tunneling machine muck, samples of machine muck were collected from nine different tunnel sites. Testing samples from a variety of tunnel sites reduces the chance of drawing erroneous conclusions about general muck characteristics. This reduction comes at the expense of the precision which could be obtained if only one type of rock were examined. For this reason trends in the variation of ϕ were observed for various types of machine muck, rather than for one large muck sample obtained from one site.

The scope of this investigation includes analyzing the variations in the angle of internal friction with variations in particle size, gradation, saturation fluids, and test-cell sizes. Standard and accepted procedures were used throughout. It was not intended to change or examine testing procedures within the scope of this investigation, but rather to use accepted procedures as specified by A.S.T.M. (1) and others.

CHAPTER 2

LITERATURE REVIEW

Much of the early testing of large-size soil materials for shear strength characteristics was done for the purpose of designing stable dam fills. Recently Marachi et al. (16) did some further studies for this purpose. Marachi conducted three series of drained triaxial tests on three different rockfill materials. His tests were conducted at 30 psi, 140 psi, 420 psi, and 650 psi using three different cell sizes (2.8-inch, 12-inch, and 36-inch diameters) and three different size consists for each material. Marachi found that compressibility seems to increase with particle size, as does the principal stress ratio at failure. He also found that for his confining pressures, cell sizes, materials used etc., the angle of internal friction decreases with an increase in confining pressure, and decreases with an increase in maximum particle size.

Koerner (11, 12) has done some work with the effect of particle characteristics on soil strength using the drained and undrained triaxial tests. In addition to offering some quantifying terms for such variables as gradation, uniformity, and sphericity, Koerner also found that the angle of internal friction increases with a decrease in particle size. Koerner was testing fairly uniformly-graded samples, and found that the increase in ϕ

increased in significance as the particle sizes became less than 0.06 mm. As a conclusion to his work, Koerner offers a prediction equation for the frictional component of the angle of internal friction:

$$\phi_f = 36° + \Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3 + \Delta\phi_4 + \Delta\phi_5 \qquad (1)$$

After defining effective size, d_{10}, to be the particle size at which 10 percent of the sample is finer, the terms of the equation can be defined. The term ϕ_f = angle of shearing resistance with dilatation removed; $\Delta\phi_1$ = correction for particle shape; $\Delta\phi_1 = -6°$ for high sphericity and subrounded shape; and $\Delta\phi_1 = +2°$ for low sphericity and angular shape. Term $\Delta\phi_2$ = correction for particle size (effective size, d_{10}); $\Delta\phi_2 = -11°$ for $d_{10} > 2.0$ mm (gravel); $\Delta\phi_2 = -9°$ for 2.0 mm $> d_{10} >$ 0.6 mm (coarse sand); $\Delta\phi_2 = -4°$ for 0.6 mm $> d_{10} >$ 0.2 mm (medium sand); and $\Delta\phi_2 = 0°$ for 0.2 mm $> d_{10} >$ 0.6 mm (fine sand). Term $\Delta\phi_3$ = correction for gradation (coefficient of uniformity, CU); $\Delta\phi_3 = -2°$ for CU 2.0 (well graded); $\Delta\phi_3 = -1°$ for CU = 2.0 (medium graded); and $\Delta\phi_3 = 0°$ for CU 2.0 (poorly graded). In addition $\Delta\phi_4$ = correction for relative density (D_R); $\Delta\phi_4 = -1°$ for $0\% < D_R < 50\%$ (loose); $\Delta\phi_4 = 0°$ for $50\% < D_R < 75\%$ (intermediate); and $\Delta\phi_4 = +4°$ for $75\% < D_R < 100\%$ (dense). Finally, $\Delta\phi_5$ = correction for type of mineral; $\Delta\phi_5 = 0°$ for quartz; $\Delta\phi_5 = +4°$ for feldspar, calcite chlorite; and $\Delta\phi_5 = +6°$ for mica.

Kirkpatrick (10) investigated the influence of grain size on ϕ by testing uniformly-graded materials and three artificially created well-graded materials. Using the drained triaxial compression test at only one confining pressure, 50 psi, Kirkpatrick found that ϕ decreased with an increase in particle size, but he could find no clear pattern for changes in ϕ with changes in gradation. Further, Kirkpatrick claims that the frictional component of ϕ, ϕ_f, is independent of particle size and grading, but that the dilatancy contribution, ϕ_d, does change with particle size. The dilatancy component, however, does not entirely account for the difference between ϕ and ϕ_f. Kirkpatrick suggests that this inconsistancy might be due to experimental or theoretical shortcomings.

Leps (14) did a review of tests for shearing strength in rockfills and found that confining pressure in triaxial tests have a marked effect on the ultimate strength (ϕ) of the material. He claims that the reason so many rock and earthfill dams have not failed over the years is that the lateral pressure involved is very low (0 to 10 psi), and the angle of internal friction is highest in this low range. As the confining pressure increases, ϕ decreases proportionally to some limiting value found at very high pressures.

Bishop and Eldin (6) have done considerable research into the effect of triaxial testing method on the resulting angle of internal friction. Their tests include drained and undrained compression and extension tests of a sand that was isotropically consolidated in some cases, and anisotropically consolidated in others. Among the results of these tests is that the angle of internal friction is independent of the magnitude of stresses. Bishop and Eldin were working with confining pressures of 100 psi or less. At higher confining pressures Mohr's envelope tends to become asymptotic to the x-axis, and this lowers ϕ. Bishop and Eldin also found that ϕ determined from drained tests can be up to 4° higher than when determined from undrained tests. Additionally, drained tests on dry samples resulted in angles of internal friction 2° to 6° higher than the saturated tests, but this large difference might be due to the drying of the sample in an oven and cooling in a dessicator. The friction angle of air-dried samples usually do not differ from that of the saturated samples by so much.

In an earlier paper, Bishop (5) studied the effects of grading, grain shape, and scale effects on ϕ as determined by shear box testing. He found from these tests that the angle of internal friction did not vary much with size, but that any differences were due to variations in loading method. Bishop did not find that uniformly-graded

materials had lower angles of internal friction than did well-graded materials. He also suggests that well-graded materials of low porosities have a higher angle of internal friction than do materials of high porosities.

Using the triaxial shear test, Leslie (15) did not find conclusive evidence that gradation or oversized particles had any influence on the shear strength. In one series of tests, he found that, at maximum bulk density, strength increased with an increase in maximum particle size, but in another series of tests he found intermediate size particles to have a greater influence on strength than large particles. In all cases Leslie concludes that the angle of internal friction increases as density increases.

Marsal (17) found that the angle of internal friction decreased with an increase in confining pressure, and that the friction angle is higher for smaller specimens. He also found considerable deviations for materials that showed a high degree of particle breakage.

Working with the triaxial compression test, Fumagalli (7) found that compression increases as particle size increases, but that the angle of internal friction decreases with an increase in size and stresses applied. Fumagalli also observed that for his tests the angle of internal friction for dry material was 1° to 2° greater than for wet. In attempting to control the void ratio

in the specimens tested, it was found that an excess of initial voids with respect to optimal conditions are to a great degree removed in the initial portions of the compression curves.

Although the related work to date has involved materials from many sources and many variations in testing method, some conclusions of the trends can be stated. Most test results agree that the angle of internal friction decreases with an increase in stress levels, and that compressibility increases with an increase in particle size for uniformly-graded material. Majority opinion seems to be, that for uniformly-graded material, the friction angle decreases with an increase in size, and that the friction angle for well-graded material will be higher than the angle for uniformly-graded material. These conclusions, along with results of tests on variations in size consist of well-graded materials, are not universally agreed upon, and are therefore treated as indicative rather than conclusive.

Spray fluids other than pure water are being considered for use with mining and tunneling machines. The two objectives of using alternate fluids are to reduce dust and to improve drillability. For dust suppression MSA Research Corporation (19) has found high expansion foam systems to be most effective. Although the ingredients of

MSA's foams are proprietary, they are basically sulfonic acids. The increased surface area of the foams upon expansion helps to attract and settle out fine particles of dust.

Work is also being done to develop surface active solutions which would improve drillability. Several theories which attempt to explain how some chemicals improve drillability are presently being explored. Robinson (22), pursuing the work of Rebinder (21), suggests that microcracks formed below the broken zone under a bit tend to heal themselves upon removal of the bit. Penetrations of these microcracks by a fluid before they have a chance to heal might reduce the free surface energy required to fracture the rock with the next passage of the bit. Robinson found sodium azelate and sodium citrate to be effective in reducing the strength of limestone and sandstone.

McGarry and Moavenzadeh (18) have done some drillability tests using various surfactants to coat the rocks. Four surfactants were tested on an actual mechanical mole owned by the White Pine Copper Company in White Pine, Michigan. While detergent (Tide) and salt ($NaCl$) solutions did not increase machine advance rate, sodium hydroxide ($NaOH$) and aluminum chloride ($AlCl_3$) were found to increase advance rate by 10-12 percent.

Other theories of increased drillability claim that some alternate saturation fluids merely cool the bit and reduce friction, thereby increasing drilling rate (28). Some solutions under investigation increase the hardness of the rock. Bits designed for use on hard or brittle materials would benefit from a hardness increase, whereas shearing type bits would require a softened material for improved performance (29).

CHAPTER 3

THEORY BEHIND METHOD OF APPROACH

Muck Characteristics

Many factors have an effect on the ultimate results obtained in testing soil materials. It is therefore mandatory that sufficient consideration be given to each step of the test procedure in order that reproducible results may be achieved. A good understanding of the soil (or muck) characteristics involved, the sampling and sieving procedures used, and the testing method employed are prerequisites to actual sample collection and testing. Without a thorough understanding of these factors, erroneous testing results are inevitable.

Several terms are commonly used in the literature to categorize muck characteristics. Familiarization with these terms and characteristics is essential to good sampling and testing procedures as well as result interpretations.

Definition of ϕ. As was mentioned earlier, the angle of internal friction relates shear strength of granular materials to the normal force acting upon it. In Figure 1(a) a normal force and a shear force are applied so that the upper particle will just overcome the friction force and lifting force required to make it move. The resultant vector force forms an angle ϕ with the normal force (13). This is the angle of internal friction. Figure 1(b) shows

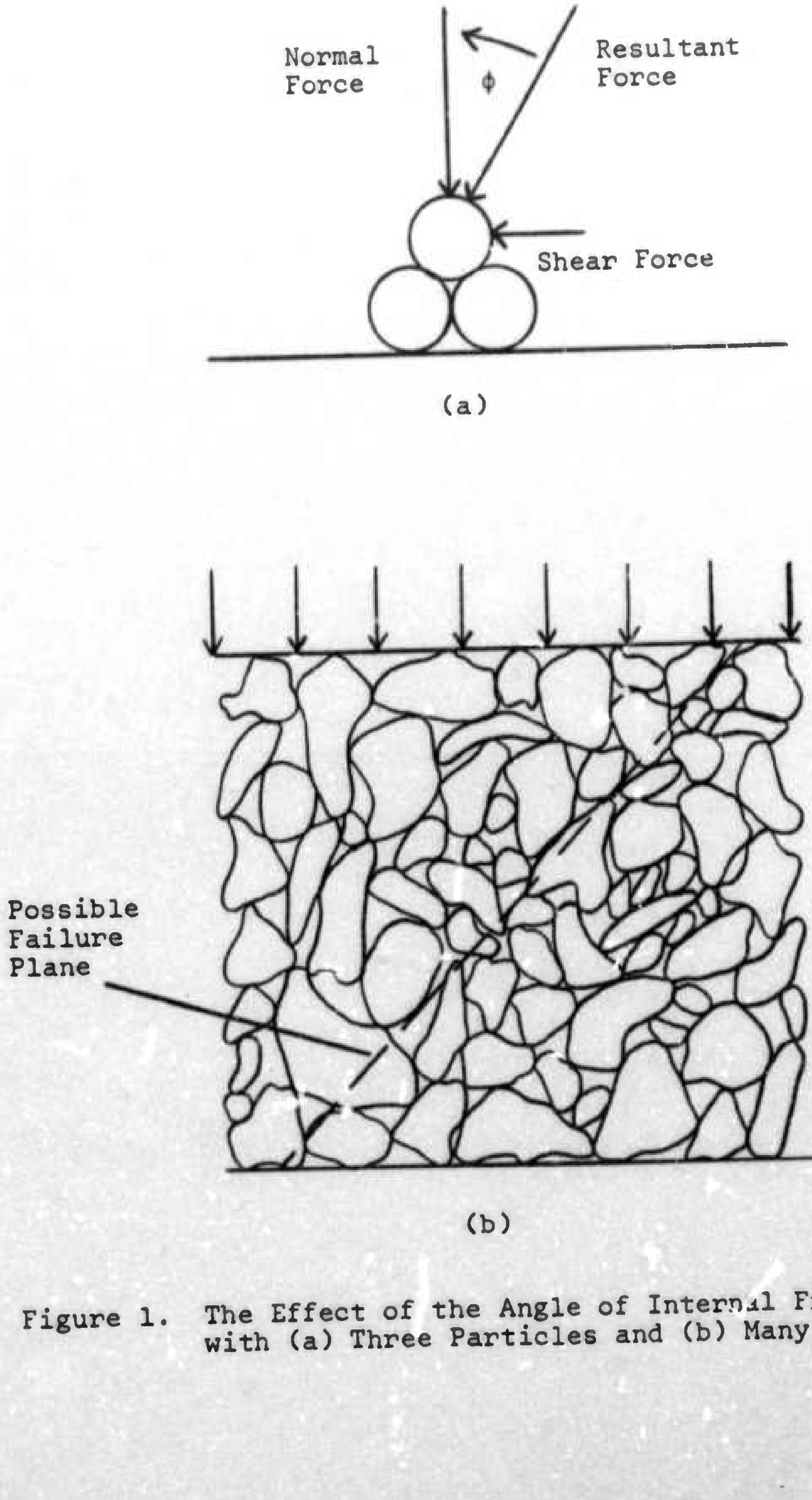

Figure 1. The Effect of the Angle of Internal Friction (ϕ) with (a) Three Particles and (b) Many Particles

a soil or muck sample being subjected to external forces. Since most of the particles are not directly above the particles below them, failure or movement will occur when the angle ϕ is reached or exceeded by many particles, often along some plane. For this reason slip planes are often visible in materials brought to failure in triaxial tests.

Since the material failure being discussed is a shear failure, it follows from Figure 1(a) that

$$\tau = \sigma \tan \phi \tag{2}$$

where τ = the shear strength

σ = the normal force

ϕ = the angle of internal friction.

Where a value for cohesion, C_0, is added to the right side of Equation (2) it becomes the Mohr-Coulomb failure equation (26, p. 391).

Mineralogy and particle shape. It is well known from the results of previous testing that mineralogy is a major factor in determining the characteristics of rock particles. Minerals of the same type will exhibit common frictional qualities even though their origins are different (16). It is therefore more important, in predicting handling characteristics, to be aware of the mineralogical constituents of the sample being tested that it is to know where the sample came from.

Particle shape and angularity also affect the angle of internal friction. Angular particles have a higher angle of internal friction then do rounded particles at a given void ratio (16). However, Koerner (11) states that particle shape and angularity is a function of mineralogy. Koerner also found that particle shape and angularity does not significantly vary with the size of the particles tested, so long as the mineralogy remains the same. It is therefore reasonable to consider only the mineralogy of the particles being tested and not to worry about particle shape, since the latter characteristic is dependent upon the former.

Size and gradation. As was mentioned earlier, former studies by Koerner (11, 12) and Kirkpatrick (10) and others indicate that in small particle sizes the angle of internal friction decreases with an increase in particle size. Of the two components of the angle of internal friction ϕ, Kirkpatrick found the frictional component ϕ_f to be independent of particle size. It is postulated that the dilatancy component ϕ_d is the component that varies with size.

Marachi finds in his literature survey that a few large particles in a well-graded sample have little or no effect on the measured strength of the sample. However, as the proportion of the larger particles increase and the specimen-diameter-to-maximum-particle-size ratio approaches

five to ten, the larger particles increase the measured strength.

Pertaining to gradation, Marachi notes at at low densities the angle of internal friction of an uniformly-graded material is higher than that of a well-graded soil. At maximum densities, however, the opposite is true. Well-graded soil has a higher angle of internal friction than does uniformly-graded material.

Cohesion. All soils can be classed in one of two groups, cohesive or cohesionless. Cohesive soils exhibit cohesion, or attraction, between individual particles, whereas cohesionless soils do not. It is important to know whether the soil being tested is cohesive or cohesionless since the method of testing each type is somewhat different from the other. Some soils are only partially cohesive. These are usually tested as though the material were cohesionless. The degree of cohesion can be measured by how high Mohr's envelope cuts the τ (shear) axis. Figure 2 shows Mohr's envelope for both a partially cohesive and cohesionless soil.

Sampling and Sieving

Several good A.S.T.M. references pertaining to sampling and sieving methods are available. Some of these can be found in the References of this paper (2, 3, 4).

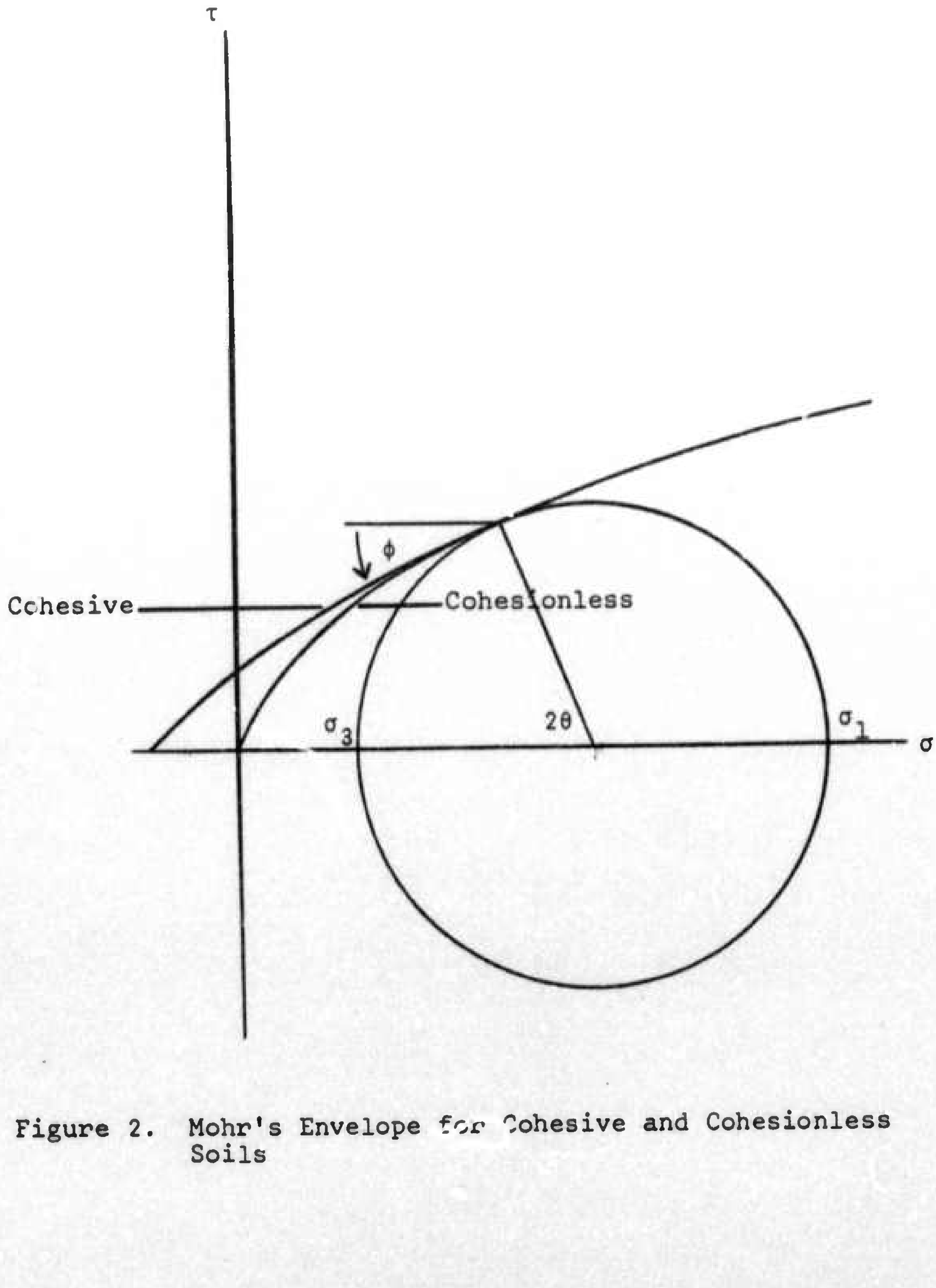

Figure 2. Mohr's Envelope for Cohesive and Cohesionless Soils

Generally, however, three basic steps may be followed in order to sample and sieve a specimen effectively.

Sampling. When a good representative sample of soil or muck is desired from a particular site, careful attention must be paid to size segregation. For example, taking a sample from a stock pile located in the open is a difficult method of obtaining a truly representative sample. Size segregation occurs during dumping, and then as the stock pile becomes subjected to weathering more segregation occurs.

A good place to sample a mining or tunneling machine is on a conveyor belt, or just as the muck passes over the tail pulley of the conveyor. Care must be taken that the muck on the entire width of a desired belt length be removed from the belt (25). Since size segregation occurs on conveyor belts, not following the above procedure gives a nonrepresentative sample. The intent of the sampling procedure is not to acquire a representative sample of the overall conditions and machine effects. If this were the case many samples from each tunnel would have been taken at intervals of perhaps one hour. The intent, however, is to obtain an instantaneous sample at given machine thrust and rpm, and geologic conditions. What is important is not the sieve analysis itself, but rather

the variations in the muck characteristics due to machine operations.

Coning and quartering. Once the sample has been moved to the laboratory, it often becomes necessary to split the sample into several smaller groups. Coning and quartering is one method of doing this. The entire sample should be slowly dumped onto a smooth clean surface, forming a cone-shaped pile. A shovel may be used to scoop up any extra soil that may not have stayed in the pile. This soil should also be dropped onto the apex of the cone. At this point the cone should be shaped into a circle of uniform thickness by pulling soil from the center of the cone straight outward to the edge of the circle. This is done to all sides of the sample until a uniformly thick circle is achieved.

The circle must now be divided into four quarters by drawing a cross (+) through the center of the circle and pulling each quarter away from the rest of the sample. Opposite quarters are recombined, forming a good representative "half" of the sample. Should these "halves" be too large for testing purposes, each half may be coned and quartered again in the same manner for further subdivisions.

Ro-tap and sieve use. The use of a ro-tap with eight-inch diameter sieves is a convenient way to sieve for gradation data, or for a large quantity of one

particular size of particle. About 500 grams of a carefully weighed sample can be put on the top screen of a six-screen stack for each cycle in the ro-tap. After about 20 minutes in the ro-tap the screens are removed and the amount of sample on each screen is weighed. The soil in the bottom pan may be weighed and run through the cycle again using smaller mesh size screens. In this way data for sample gradation curves are obtained. Larger size material (>1/4 inch) can be sieved on gravel screens and shakers. Once the weight of the sample remaining on each sieve has been determined, the sieve analysis may be presented in graphical form. Gaudin (8) offers a number of different methods of charting sizing tests. Some of the possible methods of presentation are

1. Cumulative percentage of total weight coarser <u>vs</u> screen opening.
2. Direct amount retained on each screen <u>vs</u> screen opening.
3. Direct percentage <u>vs</u> log size plots.
4. Cumulative percentage <u>vs</u> log size plots.
5. Log of the percentage in each size grade <u>vs</u> log size plots.

Each of the above plots has its advantages. Plotting the log of the screen size, as in numbers 3, 4, and 5 above, rather than plotting the screen size directly takes

into account the logarithmic nature of the screen openings themselves. This is common procedure. Number 5 above is used in studying the size distribution of crushed products. It is very similar to the Rosin and Rammler plots (23, 27) which have the log of the cumulative percentage in each size grade as the ordinate and the log size plot as the abscissa. Rosin and Rammler found this plot to be useful when dealing with crushed coal and other sufficiently pulverized materials.

The plot selected for this study is number 4 above, the cumulative percentage vs log size plot. This plot was selected because of the simplicity in understanding it, and because of its appropriateness for analysis of fairly large (up to two inches) hard-rock samples. It is used quite commonly for this purpose (5, 7, 10, 16).

Testing Method

Testing soils for the angle of internal friction can be done in several ways. The use of the triaxial cell is one effective way of obtaining this angle. Selecting the proper cell size and following proper testing procedures are critical to good testing. One advantage of the triaxial cell over the direct shear test is that the specimen being tested picks its own failure plane in the triaxial test, whereas the failure plane is predetermined in the direct shear test. Additionally, the principal stresses are known values throughout the triaxial

test, whereas they are not throughout the direct shear test.

Equipment. By varying the confining pressure in the triaxial cell for each test, the load at failure will vary. In this manner the two values σ_1 and σ_3 are obtained for plotting Mohr's circle and ultimately the failure envelope. The angle of internal friction for cohesionless soils can be obtained from one test, but if cohesion is suspected, the envelope of several tests must be plotted. The size of the specimen should be about six times the size of the largest particle to be tested. Marachi et al. (16) found that as the size of the specimen gets larger than about 1/6 the size of the cell, the measured strength of the specimen increases, especially if the specimen contains a high proportion of these large particles.

Test parameters. There are two basic types of triaxial tests, drained and undrained. In the drained test, the water in the specimen being tested is permitted to drain throughout the test, thus keeping the pore pressure of the specimen down to zero. In the undrained test all valves to the specimen are closed. Subsequent confining pressure induces a pore pressure within the sample, since the water within the pores cannot escape. The measured shear strength of a specimen will be higher in a drained test than in an undrained test (6, 13).

Strain rate must be carefully controlled during triaxial tests. A rate of axial strain of one to two percent per minute is acceptable for most tests (26) of cohesionless material. At higher rates of strain in drained tests the water within the sample cannot drain fast enough, so a pore pressure is induced. This is especially true in specimens of small particle size, or with cohesive material.

The degree of saturation of the specimen being tested also affects its strength in triaxial tests. It is therefore important that each sample being tested have the same degree of saturation, or that final calculations of strength take into account the degree of saturation. By the term "saturated sample" it is meant that the voids are filled with the saturation fluid.

Confining pressure affects density of the soil being tested. If a specimen is loosely packed but subjected to a high confining pressure, the confining pressure will have the effect of eliminating voids and thereby making the specimen more dense. Should the confining pressure be very high, the compressibility of the specimen becomes equal to the compressibility of solid particles (13). It is possible to crush some specimen particles under high confining pressure, thereby creating a failure situation before axial load application even begins.

According to Bishop and Eldin (6), a complete variation in porosity for normal cohesionless sand will result in an approximate 10° change in the angle of internal friction.

All of the above factors and conditions must be carefully handled during laboratory work with soil materials. Sloppiness or failure to properly consider everything involved in the test can lead to erroneous and nonreproducible results.

CHAPTER 4

TEST PROCEDURES

Testing Plan

After collection of muck samples for testing, but prior to actual triaxial tests, each sample was coned and quartered and then sieved for gradation analysis. These sieve analyses were used to compare variations in consist with rock type, machine type, machine parameters, etc. While coning and quartering for convenient sizes to be sieved, the material was divided also into sections to be used in various triaxial tests.

It was intended to follow three approaches in testing for the angle of internal friction. First, the variation in ϕ was determined for variations in particle size (uniformly graded) and the "combined" sample. The size fractions tested were the 6 mesh, 40 mesh, and 140 mesh. Second, variations in the gradation curve (well graded) were tested for its effects on ϕ. During the above two testing approaches the sample was always saturated with water. This procedure eliminated many questions of reproducibility of testing due to moisture content. For the third testing approach, two alternate saturation fluids were tested for their effect on ϕ. One fluid was a dust suppressor and the other was a rock weakener. During these three testing approaches, some tests were repeated

in order to determine the effect of cell size on the angle of internal friction.

Sampling and Sieving

A complete table of hard rock tunnels that were actually visited appears in Table 1. More detailed information containing a good deal of each tunnel's characteristics and drilling data appears in Appendix II. Although some of the information listed is superfluous to the tests performed here, it is nonetheless presented for general interest.

Sampling and Splitting. In as many cases as possible, samples were collected from the tunnels at the tail pulley of the conveyor belt. As has been mentioned earlier, sampling from a conveyor belt is generally good practice. Details pertaining to sampling at each particular tunnel site are available in Appendix I of this paper.

The total sample collected from most tunnels weighed approximately 100 pounds. After collection of each sample the individual samples were placed immediately into tough plastic sacks which, in turn, were contained in water-tight steel boxes. All storage and transportation of samples was in these boxes. Each sample was coned and quartered according to good splitting practice as discussed in the previous chapter. One-half of the sample was then set aside for possible future testing in the six-inch cell. Of the remaining one-half sample, one-quarter

Table 1. Tunnels Sampled

Name	Contractor	Diameter	Rock Type	Location	Completion	Machine
Queen Lane Raw Water Conduit	S & M Contractors	11'	Mica Schist & Quartz	Philadelphia, Pennsylvania	Aug. 71	Jarva Mark 11-1100
Navajo Irriga-tion	Bu. Rec. with Fluor Utah Eng. & Con.	20-1/2'	Sand-stone	Farmington, New Mexico	April 72	Dresser
Currant Creek	S. A. Healy Co. for Bureau Rec.	13'	Sand-stone	Heber City, Utah	1972	Robbins 141-1
Toronto Inter-ceptor Sewer	S. McNally & Sons, Ltd.	12'	Shale	Toronto, Canada	Fall 71	Robbins 126
White Pine	self	18'	Sand-stone (1971) Shale (1972)	White Pine, Michigan	--	Robbins
Nast	Bureau Rec. with Peter Kiewit	10'	Granite	Aspen, Colorado	--	Wirth
Lawrence Avenue	McHugh Construction	13'8"	Dolomitic Limestone	Chicago, Illinois	Oct. 71	Lawrence

Table 1 (Continued)

Name	Contractor	Diameter	Rock Type	Location	Completion	Machine
Moss Point Drainage System	S & M Contractors	14'3"	Shale	Euclid, Ohio	--	Jarva Mark 12-1403
North Branch Interceptor Sewer Conduit	Perini	11'	Mica Schist	New York City	--	Jarva Mark 12

was dried in an oven at 200°F for 24 hours and then part of this sample was sieved for a gradation analysis. The remainder of the quarter was saved for "combined" (i.e., not sieved) testing in the 2.8-inch or six-inch triaxial cell. After studying the results of the gradation analysis the individual sizes to be tested were selected. The remaining one-quarter of the entire sample was then sieved for bulk quantities of the individual sizes to be tested.

Sieving. Eleven, eight-inch diameter, brass U.S. Standard sieves were used in sieving all samples. The sieve sizes used (in inches) were 2, 1, 0.5, 0.25 (3 mesh), 0.132 (6 mesh), 0.0661 (12 mesh), 0.0331 (20 mesh), 0.0165 (40 mesh), 0.0083 (70 mesh), 0.0041 (140 mesh), and 0.0021 (270 mesh). Every sample sieved passed the two-inch sieve, so the maximum size sieve was properly chosen. Although a portion of each sample passed the 270-mesh-sieve into the bottom pan, smaller-opening sieves were not deemed necessary. Triaxial testing of size fractions would be done on the plus-270-mesh sizes since it is these sizes that can most easily be varied by altering tunneling machine parameters such as thrust and speed.

The sieving for gradation analysis was repeated four times for each tunnel sample. Since the results of the sieve analyses for each tunnel were always close, the results of the four tests were averaged together in each case.

The Triaxial System

The triaxial cells used in the testing are capable of handling specimens 1.4 inches in diameter, 2.8 inches in diameter, and six inches in diameter. The triaxial equipment acquired for the testing was purchased from Soiltest, Inc. of Evanston, Illinois. It was decided not to purchase the confining pressure or loading system since available Pennsylvania State University facilities could be adapted to serve these purposes. The pressure and electrical systems therefore had to be designed and built before the actual testing began. A photograph of the entire testing system is shown in Figure 3. Visible are the 2.8 inch cell, the load cell, molds, the movable cart, the control panel, input conditioner, strip chart recorder, and a junction box.

Pressure System. A block diagram of the final pressure system design appears in Figure 4. An air supply capable of pressures up to 75 psi was used to pressurize the glycerin tank. A mobile cart was designed to carry the tank and an accompanying control panel. Since the loading system is a Baldwin hydraulic press used also in other research projects, the cart simplified the quick disengagement of the triaxial system from the press without disturbing the calibration of the system.

Four valves were used on the triaxial cell itself. Two of these were used for saturating the specimen with

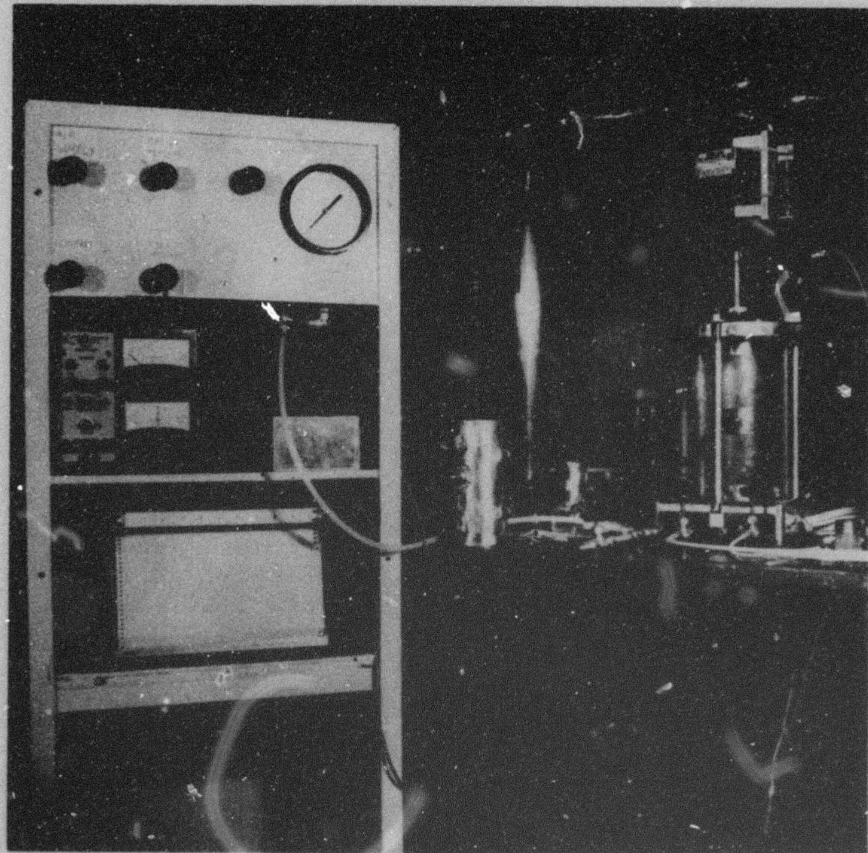

Figure 3. The Test System

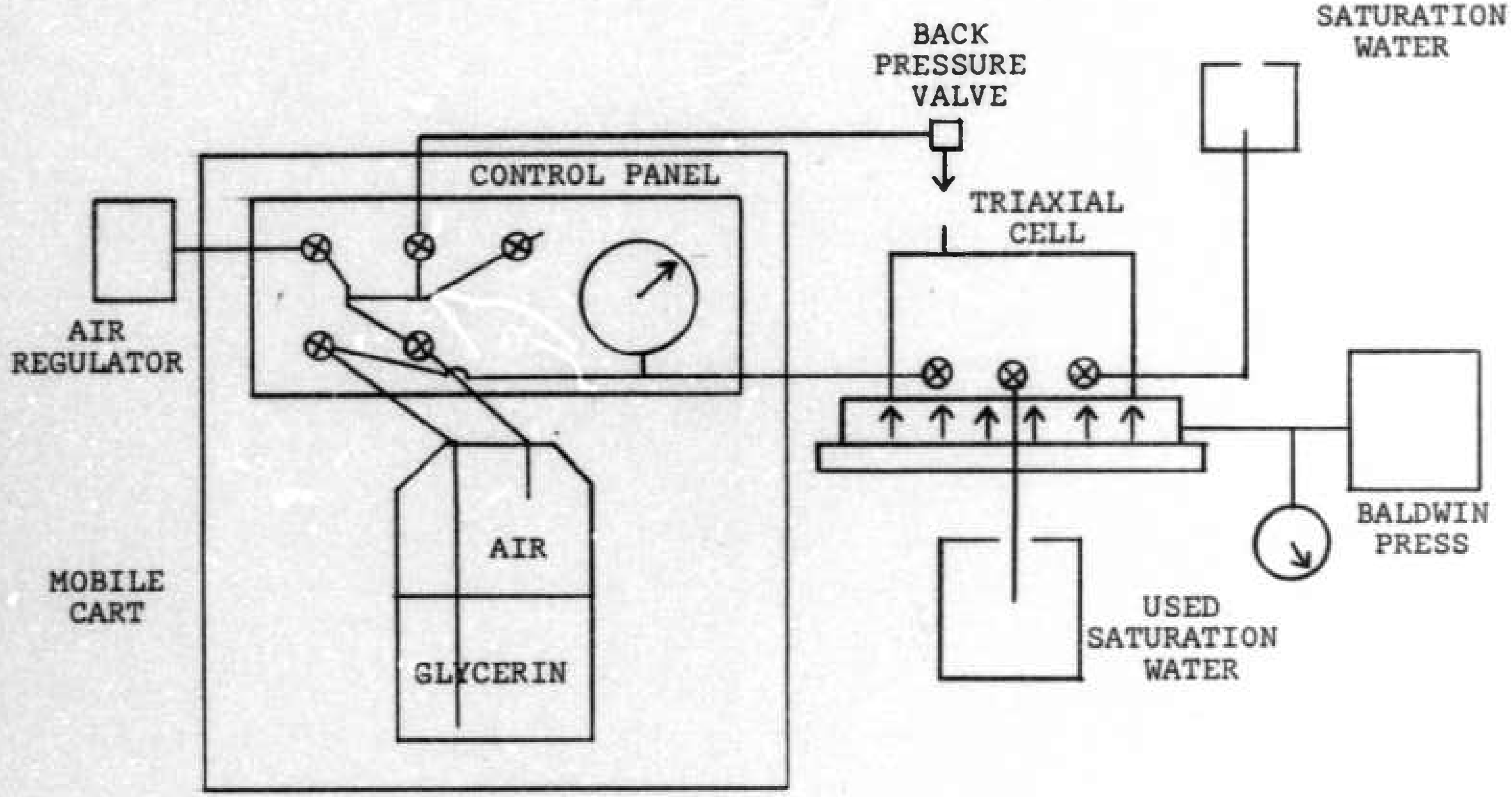

Figure 4. Block Diagram of the Pressure System

water. Water was permitted to enter through a valve to the bottom of the specimen. At saturation the water flowed out of the top of the specimen, through a valve, and into a bucket outside the system. At this point the water supply valve was closed, but the drainage valve remained open throughout the test. Since the degree of saturation affects the test results, it was decided to run all tests at 100 percent saturation in order to maintain uniformity. In that the muck coming from the face of a tunnel being bored can be quite wet since boring machines use water for cooling and dust control purposes, it was felt that saturation was a better simulation of actual conditions than testing dry. Any other state of moisture content would be difficult to simulate in as much as there is a rapid change of voids ratio near failure.

The valve on the top of the cell was used primarily for back pressure when draining the cell, or occasionally as a pressure release valve. The remaining valve at the base of the cell was used for glycerin filling and draining. Since the specimens tested never failed so dramatically as to contaminate the confining pressure fluid, the glycerin was always drained directly back into the glycerin tank. Filtering was not necessary.

Finally, a Baldwin press was used for axial load application. Although the press is equipped with a guage for measuring load, this was used only as a visual

reference since the electrical system provided for this measurement.

Electrical System. A block diagram of the electrical system appears in Figure 5. Figure 6 is a more detailed schematic of the system. The two power supplies and the junction box are all located on the mobile cart. As can be seen in Figure 5, the entire electrical system can be unplugged from the load cell and linear potentiometer without disturbing the rest of the system.

The use of an input conditioner as a power supply for the load cell is very convenient. Calibration and zeroing features of the conditioner permit checks of the entire electrical system, even during a test, without disturbing the test itself. Both the input conditioner and the constant voltage power supply were maintained at 10 volts d-c for all tests. The scale settings on the chart recorder, however, were varied as needed throughout the testing program. By reducing the scale of the recorder output, more accurate readings are possible for 1.4-inch, or low strength specimens. The scale must, of course, be increased for 2.8, or high strength specimens.

The load cell used to measure load applied vertically is a BLH (Baldwin-Lima-Hamilton) transducer capable of measuring loads between 0 and 10,000 pounds. The output of the load cell is three millivolts per volt of input at 10,000 pounds load. It was decided to apply 10 volts

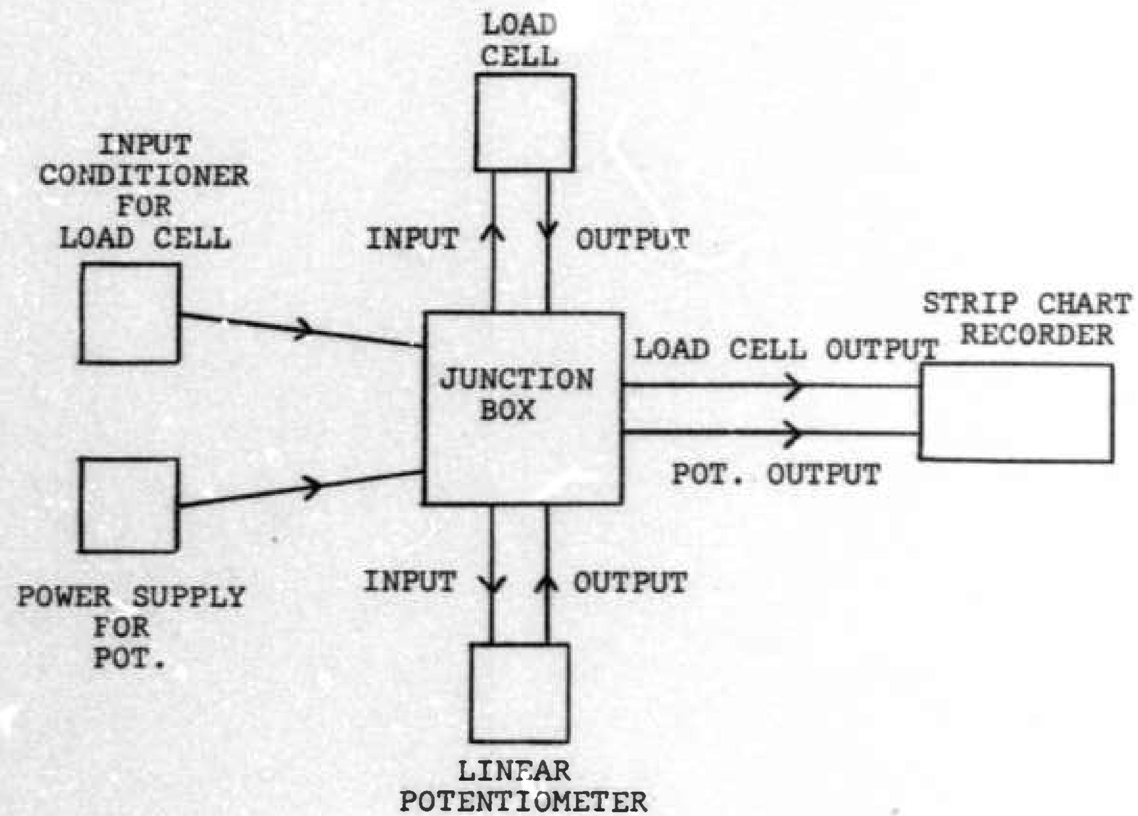

Figure 5. Block Diagram of the Electrical System

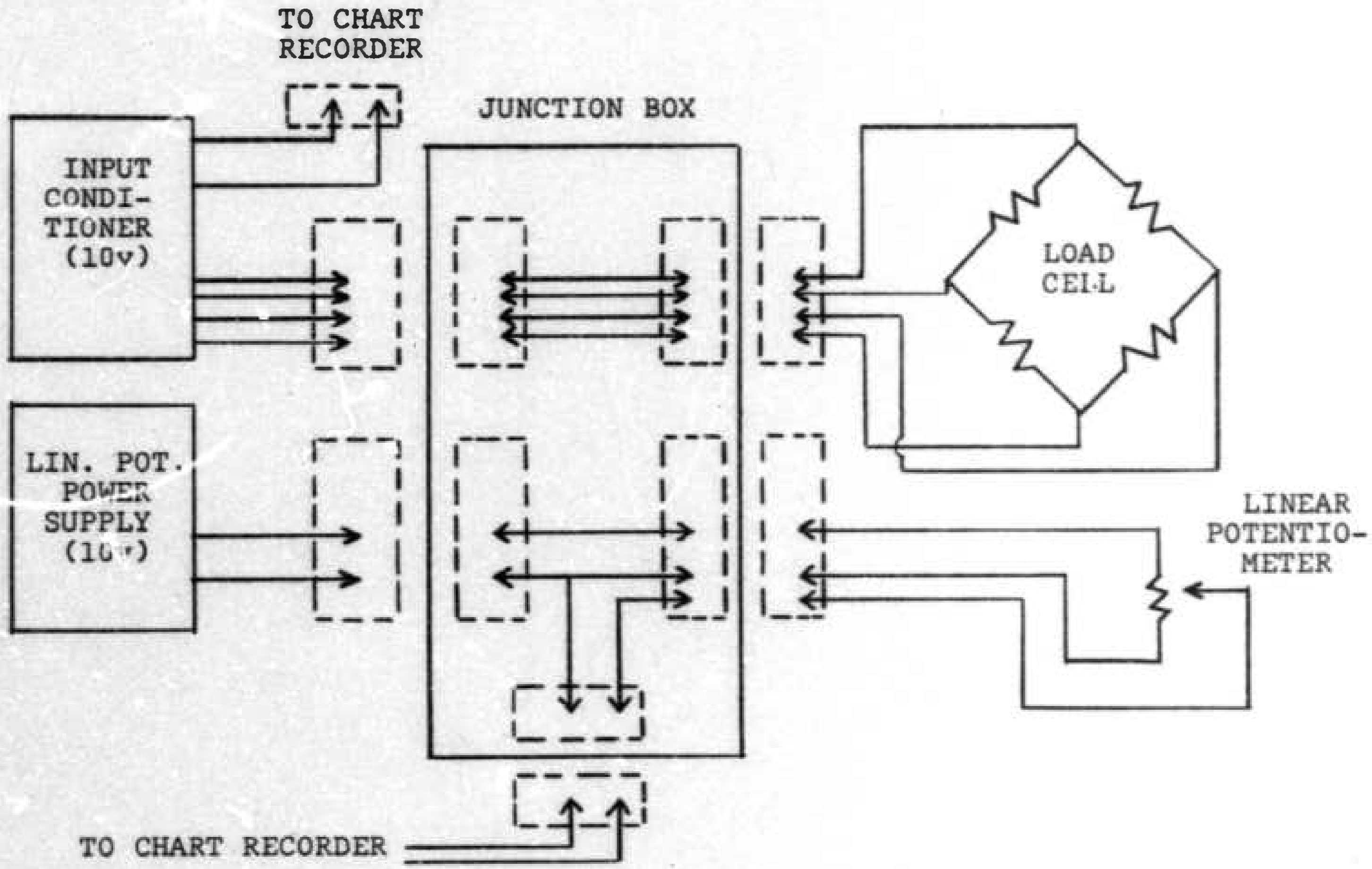

Figure 6. Schematic of the Electrical System

to the load cell so that the output would be in the zero to 30 millivolt range. The need for a 10,000 pounds capacity load cell was based on the assumption that maximum load would occur at a confining pressure or 70 psi (the maximum available) when using the six-inch cell. Assuming a high angle of internal friction (40 degrees was selected), one Mohr's circle was drawn through 70 psi and tangent to a 40 degree line drawn through the origin. The resulting load in psi converted to just under 10,000 pounds in vertical force. The load cell purchased was calibrated at the factory in November, 1971, and then calibrated again in January, 1973. This second calibration test was performed on the MTS loading system located in the Mineral Engineering Department of The Pennsylvania State University. The maximum error was found to be 0.25 percent at 10,000 pounds load. This small deviation warranted no adjustment in the electrical equipment or calculations performed.

The purpose of the linear potentiometer is to measure the strain rate of the material during deformation. Calibration of the linear potentiometer showed a voltage change of 0.45 volt per volt input per inch of deformation. Applying 10 volts to the potentiometer, the readout voltage converts to 4.5 volts per inch of deformation. The potentiometer was found to be almost perfectly linear through its 2.2-inch stroke.

A two-channel Hewlett-Packard strip chart recorder was purchased for the recording of strain rate and vertical load. The strip chart recorder was calibrated upon delivery in August, 1971, and then again in January, 1973. The error in the strip chart was found to be less than two percent during the second calibration. This error was corrected and testing was resumed.

Before testing began each day, the output of the two power supplies was measured with a voltmeter. Any deviations from the 10 volts required from each power supply was immediately corrected. With the proper voltage inputs to the load cell and linear potentiometer, the range of the outputs to the chart recorder would be from zero to 30 millivolts for the load cell and from zero to 10 volts for the linear potentiometer.

Steps in testing. The materials gathered from the first seven tunnels shown in Table 1 (that is all but the Cleveland and New York samples) were the first to be tested. These samples were tested for the angle of internal friction of the material as it came off the belt (the "combined" sample), and for the angle of internal friction of each of the three selected size fractions (6 mesh, 40 mesh, and 140 mesh). This involved over 75 individual triaxial tests using three different cell sizes. Each test takes about 1/2 day to perform. Figures 7 and 8 show two of the cell sizes used for testing. Figure 7

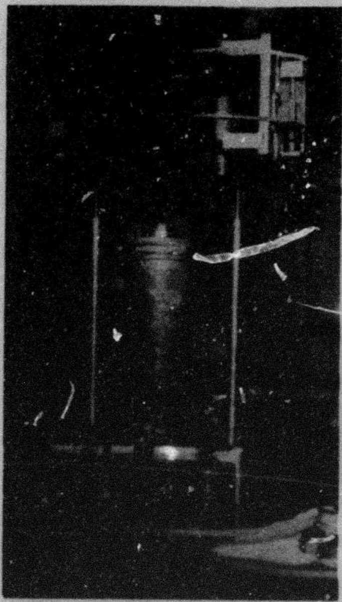

Figure 7(a). 2.8-Inch Specimen Before Testing

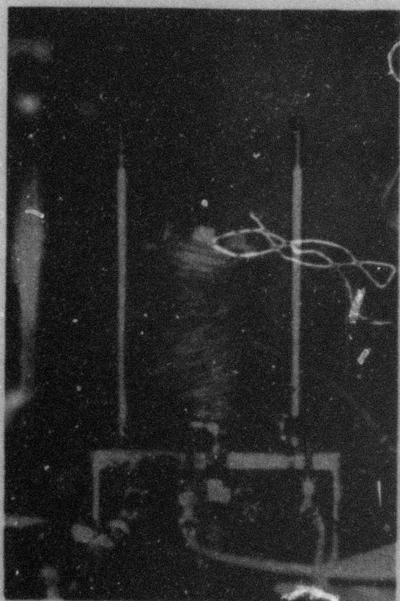

Figure 7(b). 2.8-Inch Specimen After Failure

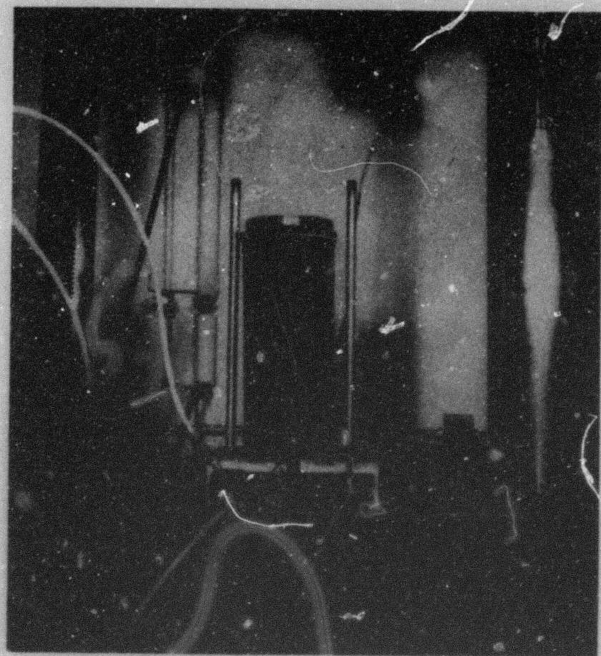

Figure 8(a). 6-Inch Specimen Before Testing

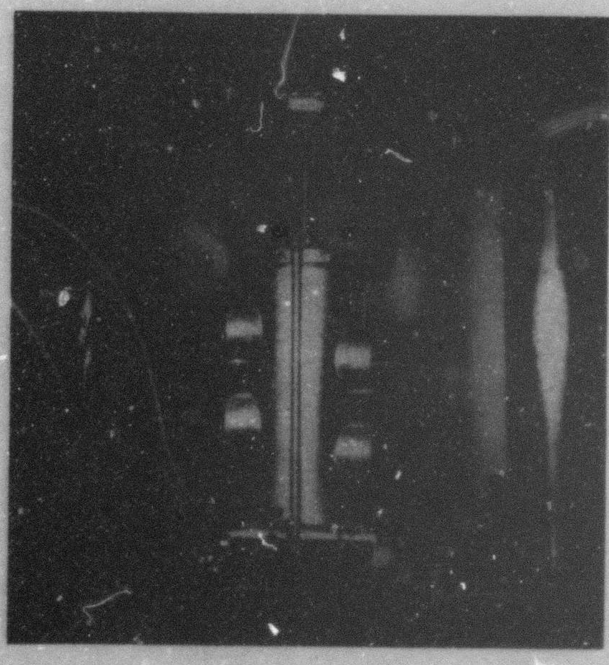

Figure 8(b). 6-Inch Specimen During the Test

shows the 2.8-inch specimen before and after testing, and Figure 8 shows the six-inch specimen before testing and during a test.

All tests performed were drained triaxial tests, and the samples were saturated with water. It was learned from these tests that the competent noncohesive materials (such as granite and mica-schist) gave fewer drainage problems than cohesive or friable materials (such as shale or weak sandstone). Friable material breaks down during testing, and cohesive material has a tendency to build up pore pressure. Both of these conditions make it difficult to reproduce results, or to vary some parameters while maintaining others constant. A competent noncohesive material was therefore selected for the next series of tests.

The second series of tests performed involved 12 individual triaxial tests during which size consist of the material being tested was varied in order to determine the effect of changes in consist on the angle of internal friction. Varying size consist has been done by others (7, 10, 16), but there does not appear to be any standard method of performing this variation. Since this entire study is concerned with tunneling machines, an attempt was made to collect several samples from one machine under variations in machine parameters. The Navajo tunnel near Farmington, New Mexico was selected for this collection

since the machine there is d-c powered. Although most tunneling machines can vary their cutter head thrust, only d-c machines can also vary their cutter head rotation speed. By varying the cutter head speed and thrust, it was hoped that a machine variation in size consist could be obtained. Five samples of approximately 200 pounds each were obtained under variations in machine parameters. The small variations are shown in Table 2. A plot of the sieve analyses of these five samples is shown in Appendix III of this paper. Since four sieve analyses were actually performed on each sample in order to determine the gradation curve, a statistical analysis was performed in order to determine the degree to which the curves differed. Using Student's t Distribution, and requiring a 95 percent confidence that the curves are different, it was found that the three curves are not different to the 95 percent degree of confidence. Consequently, it was decided that consists of greater differences would have to be mixed.

As was mentioned earlier, the materials that respond best to triaxial testing are the competent noncohesive materials. The Manhattan schist (mica schist) is such a material. A sieve analysis of the mica-schist sample collected from the New York tunnel is shown in Appendix III. By multiplying each particle size by four and then

Table 2. Operating Parameters of Navajo Tunnel Machine for Specimen Collection

Sample No.	Machine Thrust	Cutter Head RPM
1	1,090,000 pounds	8
2	850,000 pounds	8
3	612,000 pounds	8
4	1,090,000 pounds	7
5	1,090,000 pounds	5

dividing each particle size by four, two additional sieve curves can be generated as shown in Figure 9. The factor four was selected because Student's t Distribution performed on the original curve required a factor of at least four in order to achieve 95 percent confidence that the curves are indeed different. Once these additional two size consists were mixed, triaxial testing in the six-inch cell (saturated, drained) of all three size consists commenced.

The third series of tests involved 40 individual triaxial tests with the purpose of determining the influence of alternate saturation fluids on the angle of internal friction. As was mentioned earlier, a dust suppressor and a rock softener were selected as alternate saturation fluids since both are being studied for use in mines and tunnels. For dust suppression, a sulfonic acid solution similar to Avirol-200 (sodium lauryl sulfate) is being studied by MSA Research (19). It has been found to be very effective when mixed to a one percent solution in water. A sufficient quantity of this solution at one percent concentration was prepared and used as the saturation fluid. For rock softening, sodium citrate mixed to a two percent solution in water has been found to be effective in some cases (22). A sufficient quantity of this solution at two percent concentration was also prepared to be used as a saturation fluid.

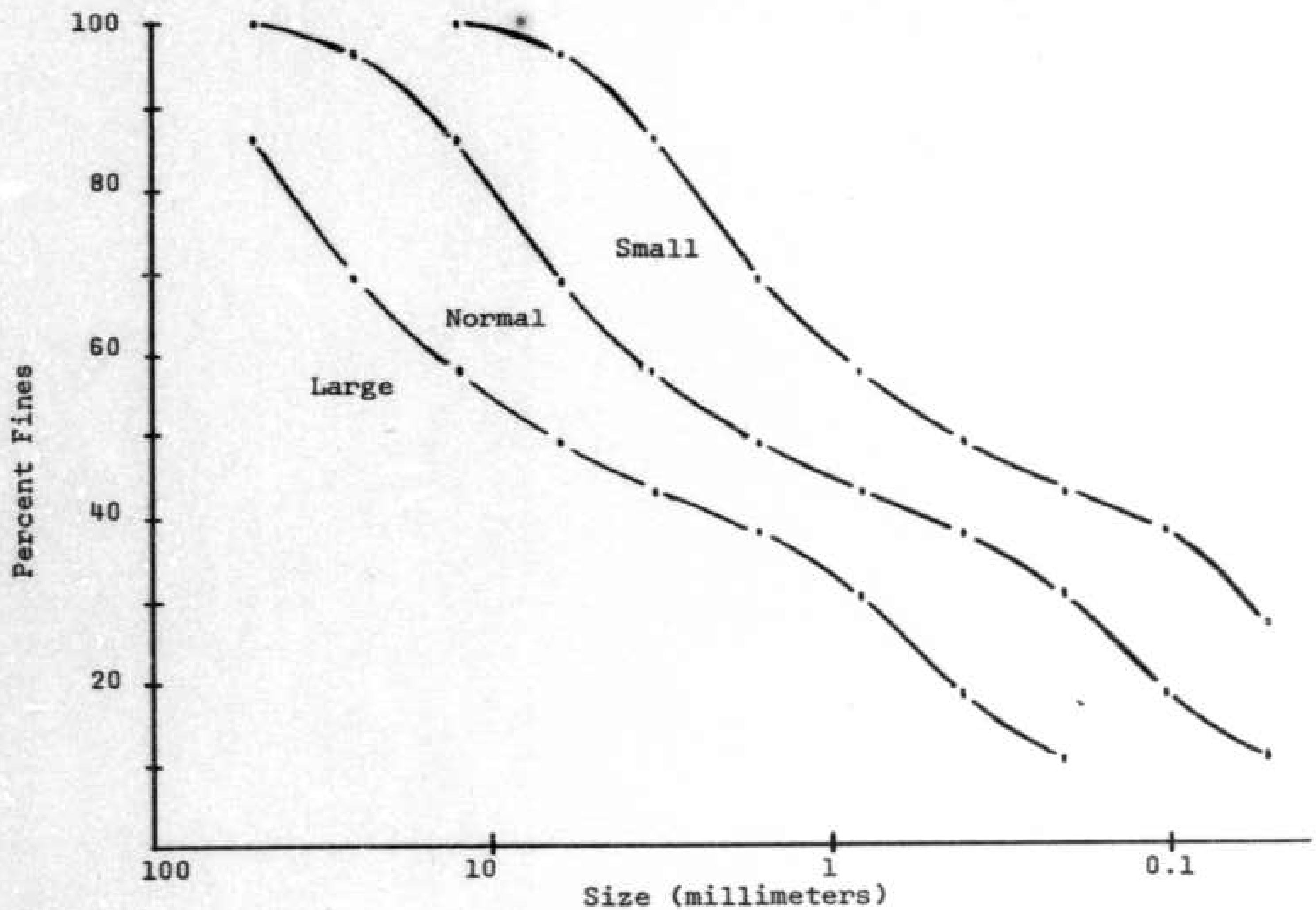

Figure 9. Sieve Analysis Curves for Large, Normal, and Small Consists of the New York Material

Since the muck samples collected from the tunnels vary from competent, noncohesive to incompetent and very cohesive, the above saturation fluids were tested on muck samples representing each group. The muck used in these tests were the Cleveland sample (cohesive, incompetent shale) and the New York sample (noncohesive, competent mica-schist). All tests were performed in the 2.8-inch cell. Since the only varying parameter is the saturation fluid, the use of the large cell along with the full range of particle sizes was not required. For tests in the 2.8-inch cell, all material larger than 1/2 inch was scalped from the sample in order to maintain a six-to-one ratio of cell size to maximum particle size (16). In order to maintain a control, however, the tests of alternate saturation fluids in the 2.8-inch cell also included tests of the materials saturated with water, and tests of the air-dried materials; i.e., no saturation fluid.

Marachi (16) has examined the effects of cell size on the angle of internal friction and found it to be minor. In this study the small materials (6 mesh, 40 mesh, and 140 mesh) were usually tested in the 1.4-inch cell, and the combined materials were tested in the 2.8-inch or six-inch cell. Some tests of like materials were duplicated in other cell sizes just to verify Marachi's conclusions. Tests of the Chicago, Toronto, and White Pine

six mesh materials in both 1.4-inch and 2.8-inch cells were conducted, in addition to the tests of the New York combined materials in both the 2.8-inch cell and the six-inch cell.

In plotting Mohr's envelope for granular materials, it is best to run at least three tests on the same type of material at varying confining pressures (see Chapter 3, Testing Methods). To improve accuracy, four tests at confining pressures of 15, 30, 45, and 60 psi were used in the tests for this study. Low confining pressures were selected in order to best simulate the low confining pressures which actually exist in materials handling systems. Four typical superimposed strip chart test data are shown in Figure 10. Four Mohr's circles are drawn from these data. In most other research a wider range of confining pressures is used in triaxial testing. This wide range of pressures tends to make the Mohr's circles drawn fit a tangent line better. Conversely, the narrow range of tests used in tests discussed in this report tend to increase the irregularity of the Mohr's circles drawn. For this reason four tests of each sample (instead of three) are performed.

The actual testing procedure is unaffected by the specimen size, cell size, or saturation fluid being used. A listing of the steps in testing is therefore common to every test performed.

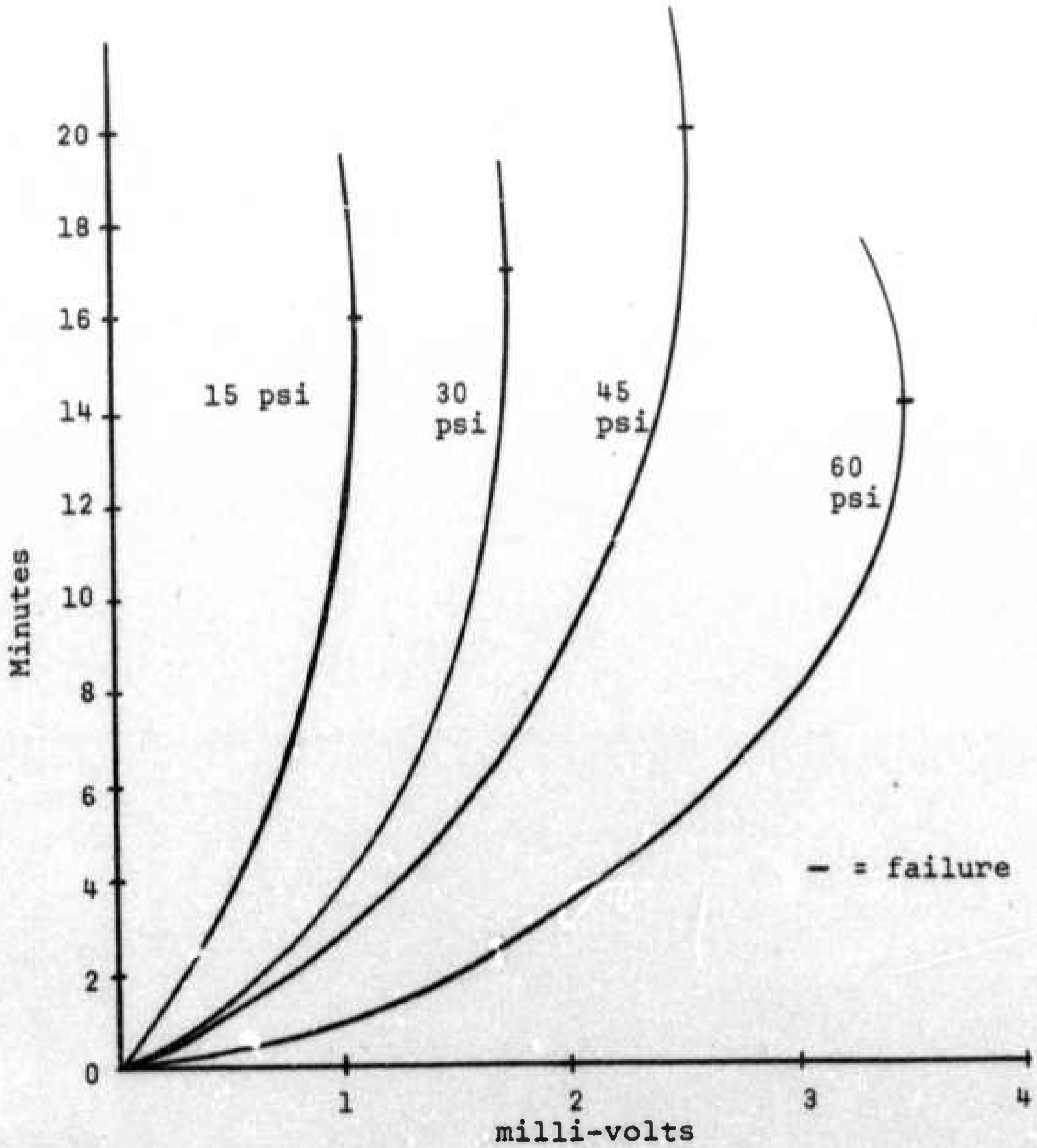

Figure 10. Strip Chart Data for New York Material Saturated with Water

1. The two rubber gaskets which seal the cell are cleaned, greased with high pressure vacuum grease, and seated in their proper grooves.

2. Grease is then applied to the sides of the brass base onto which a porous stone is placed.

3. A membrane is placed over the porous stone and brass base and sealed tight with rubber bands.

4. Next a mold is clamped around the membrane and the top of the membrane is folded over the top of the mold.

5. A vacuum pump is used to evacuate the air between the membrane and the mold in order to form a good cylinder.

6. The sample is placed within the membrane in 1/2 inch layers and gently tamped to the desired density. This tamping procedure is maintained constant for all samples and roughly approximates the compaction that would be received under normal handling; namely, that due to the impact experienced at transfer points. No attempt was made to achieve minimum porosity or overconsolidation.

7. The upper porous stone is then placed on top of the sample within the membrane.

8. Vacuum grease is then applied to the upper plate, placed on top of the porous stone, and sealed by the membrane with rubber gands again.

9. The vacuum pump is turned off and the mold is removed from the sample.

10. Final checks are made using a bubble level to insure that the specimen stands perfectly vertical and that the upper plate is horizontal.

11. Assembly of the triaxial cell is completed by properly positioning the cylindrical body of the cell and securely bolting down the cast iron top of the cell.

12. The Baldwin press is then adjusted so that the load cell just meets the fully extended loading piston, and the extended arm of the linear potentiometer just touches the top of the triaxial cell.

13. The specimen is saturated by opening the water supply valve and the drainage valve. When water starts to come out of the drainage valve the water supply is cut off and the specimen is allowed to equalize pore pressure to zero through the drainage valve.

14. Pressure is then applied to the glycerin tank and glycerin is permitted to flow into the cell until the specimen is entirely covered and the desired confining pressure is reached.

15. Pressure equilibrium between the glycerin tank and the triaxial cell is achieved and maintained throughout the test. (The cell and tank are open to each other during all tests.)

16. Final zeroing calibrations are applied to the chart recorder.

17. The Baldwin press is then turned on and the strain rate adjusted to about 1.5 percent per minute.

18. When the load recorded on the chart recorder begins to decrease despite continued axial strain the specimen is considered to have failed and the Baldwin press is turned off.

19. Air pressure is bled off at the top of the glycerin tank and back pressure is applied to the top of the triaxial cell. In this way the glycerin in the cell is forced back into the tank.

20. All pressures are reduced to zero and the triaxial cell is unbolted and opened up.

21. The specimen is removed and the entire apparatus is wiped clean in preparation for the next test.

CHAPTER 5

TESTING RESULTS

Introduction

The results of all the testing done can be put into two categories: sieve analysis results, and triaxial test results. Although the triaxial test results are important in terms of the purpose of this study, the sieve analysis results might be of just as much importance to a tunneling machine manufacturer or tunneling contractor.

Sieve Analysis Results

Table 3 shows the percentage retained on each sieve for the sieve analysis of every tunnel visited. Table 4 compares machine, cutter, and rock type with rock size. Plots of the log of the particle size vs cumulative percentage finer for each tunnel visited appear in Appendix III of this paper. Although all but one tunnel visited (Nast) used disc type cutters, it seems apparent that disc cutters tend to produce larger size consists than do button rollers (see Table 4). Additionally, single disc cutters seem to produce larger size consists than do double disc bits.

During the second visit to the Farmington tunnel an attempt was made to vary size consist by changing machine thrust and cutter head speed. Although only a few variations in machine parameters were made, it appears

Table 3. Tabulated Sieve Analysis (Percentage Retained on Each Sieve)

a. Analysis for Philadelphia, Farmington (1971), Heber City, Toronto, White Pine (1971), Nast, Chicago Tunnels

	Phila.	Farmington ('71)	Heber City	Toronto	White Pine ('71)	Nast	Chicago
2"	0	0	0	0	0	0	0
1"	0	5.9	4.9	9.0	33.4	0	4.2
1/2"	8.1	8.8	10.7	38.6	16.9	4.1	22.2
3 mesh	4.5	7.2	12.7	11.2	25.7	7.8	26.2
6 mesh	8.3	5.6	15.6	15.7	5.2	10.3	15.0
12 mesh	8.4	3.9	15.6	11.0	3.5	12.1	10.5
20 mesh	10.0	6.8	11.8	5.7	2.5	11.4	6.0
40 mesh	12.5	18.7	8.3	3.0	2.0	11.8	3.7
70 mesh	17.9	21.7	5.9	1.6	2.3	11.2	1.8
140 mesh	15.9	11.8	6.0	1.1	3.9	9.7	1.2
270 mesh	7.2	5.2	3.9	0.8	2.3	7.2	1.9
Passed All Sieves	7.2	4.4	4.4	2.3	2.3	14.4	7.3

Table 3 (Continued)

b. Analysis for Farmington (1972), White Pine (1972), Cleveland, New York Tunnels

	Farmington ('72)					White Pine ('72)	Cleveland	New York
	1	2	3	4	5			
2"	0	6.8	6.0	0	5.3	0	0	0
1"	17.1	24.0	4.9	29.5	25.8	14.5	0	3.3
1/2"	15.2	16.8	15.3	11.6	15.1	22.1	16.3	10.4
3 mesh	7.0	4.7	4.9	3.9	5.3	23.3	24.6	16.8
6 mesh	4.1	2.8	3.2	3.0	5.4	12.8	13.4	11.4
12 mesh	4.0	2.7	3.3	3.4	2.7	8.7	12.5	9.0
20 mesh	8.0	6.3	6.9	7.5	6.2	5.0	10.2	6.1
40 mesh	16.0	13.1	13.0	15.3	13.5	3.9	7.0	4.8
70 mesh	15.0	12.4	11.9	14.2	12.8	3.1	4.8	7.4
140 mesh	7.6	6.0	6.0	6.8	6.2	2.8	3.3	12.0
270 mesh	3.1	2.5	2.6	2.8	2.5	2.0	1.9	7.8
Passed All Sieves	2.9	1.9	2.0	2.2	2.2	1.8	6.0	11.0

Table 4. Comparison of Machine Type and Rock Size

Tunnel	Machine	Cutter	Rock Type	Smallest Sieve Through Which More Than 50% Passed
Phila.	Jarva Mark 4	27 Disc Kerf	Mica Schist	20 mesh
Farmington(1971)	Dresser	36 Double Disc	Sandstone	20 mesh
(1972)				
1	"	"	"	12 mesh
2	"	"	"	1/2 inch
3	"	"	"	1/2 inch
4	"	"	"	6 mesh
5	"	"	"	1/2 inch
Heber City	Robbins 141-127	29 Disc	Sandstone	6 mesh
Toronto	Robbins 126	25-30 Disc	Shale	1/2 inch
White Pine (1971)	Robbins 181-122	47 Disc	Sandstone	1 inch
(1972)	"	"	Shale	1/2 inch
Nast	Wirth 600	26 Button Rollers	Granite	20 mesh
Chicago	Lawrence 0007	27 Disc with Button Mount	Dolomitic Limestone	1/2 inch
Cleveland	Jarva Mark 12	Multiple Disc	Shale	3 mesh
New York	Jarva Mark 12	Disc with Carbide Inserts	Mica Schist	6 mesh

that reduced cutter head speed and machine thrust increases size consist. The size change was not statistically significant, however, and the change in machine advance rate could not be determined. It does appear that small changes in size consist can be achieved through variations in machine cutter head speed and thrust, but in order to drastically change size consist a change to an alternate bit type is required.

The White Pine Copper Mine in northern Michigan was visited in July, 1971 and again in July, 1972. Although machine type, bit type, thrust, rpm, etc. were identical from one year to the next, the rock type varied. In 1971 the machine was in a hard sandstone, and in 1972 it was in a shale. Although the size consist of the 1971 sample was a bit larger than the 1972 shale sample, the two curves were quite close and similar.

Another interesting comparison is that of the Philadelphia tunnel and the New York tunnel. Both were using similar Jarva machines of the same diameter, thrust, rpm, etc. Both were also boring through very competent mica-schist formations (10,000-30,000 psi compressive strength) but the bits used were slightly different. The Philadelphia tunnel used disc kerf bits and the New York tunnel used steel disc bits with carbide inserts. The sieve analysis of the New York material showed a size consist considerably larger than that of

the Philadelphia. It should be mentioned that bit type cannot be singled out as the only difference between these tunnels. The differences in rock characteristics, machine parameters, etc. at the actual time of collection might also vary somewhat. As one last comparison, the differences in consist between the Farmington 1971 sample and the sample 1 from the 1972 trip indicate some dependence on geology. The machine parameters were the same but the sieve analyses are quite different. It is impossible to nail down every variable, but the above trends in consist changes can be pointed out.

Triaxial Test Results

Based on the information shown in Table 5 it can be said that for competent, noncohesive muck the angle of internal friction appears to decrease with an increase in particle size when individual size fractions are being tested. The variations from the largest material tested (6 mesh) to the smallest (140 mesh) never exceed 5°. For cohesive material saturation with water produced the opposite effect. With the smaller size particles ϕ decreased to 0°. This could be due to the inability of the sample to relieve itself of induced pore pressure during testing, and to the breakdown of the material into a fine frictionless clay. It is felt that these same problems would occur during materials handling processes.

Table 5. Tabulated Angles of Internal Friction (in Degrees) with Variations in Particle Size, Size Consist, and Saturation Fluids

Particle Size	Combined	6 mesh	40 mesh	140 mesh
Philadelphia*	28.5	29.0	32.0	34.5
Farmington	30.0	--	38.0	32.0
Heber City	0	--	0	0
Nast*	37.0	27.0	28.0	29.0
Chicago*	38.0	27.5	31.5	32.0
Toronto	21.5	27.5	0	0
White Pine	33.0	29.5	27.4	24.5

Size Consist	Large	Normal	Small
New York*	34°	31°	25°

Saturation Fluids	Dry	Water	Detergent	Sodium Citrate
New York*	32°	32°	30°	27°
Cleveland	32°	0°	0°	0°

*Competent non-cohesive material.

In five out of seven tests, the combined material showed a higher ϕ than most of the individual size fractions.

For materials tested with variations in size consist, the angle of internal friction increased with an increase in size consist as is shown in Table 5. From the smallest size consist to the largest (each particle being varied by a size factor of 16) the ϕ angle increased by 10°. The material tested was the competent Manhattan schist from the New York tunnel and was saturated with water. If a cohesive material such as a shale had been tested the angle ϕ would most certainly have dropped drastically with a decrease in particle size.

Table 5 also shows the effects of two saturation fluids (detergent and sodium citrate), as compared with water and no saturation fluid, on the New York and Cleveland combined materials. The Cleveland material, being a shale, showed strength only when tested dry. The New York material showed a decrease in strength when tested with the detergent solution, and an even greater decrease in strength when tested with sodium citrate.

A few additional tests were randomly performed on the same material using different cell sizes. The results of these tests and all other tests performed are available in Appendix IV and Appendix V of this report. Marachi (16) claims some slight variations with cell size, but the variations noted at the confining pressures

used in this study sho ed no consistent trend or dramatic variations. Consequently, so long as the maximum particle size to cell size ratio does not get too large (Marachi suggests $\leq 1/6$) the cell size does not appear to appreciably affect the angle of internal friction.

CHAPTER VI

CONCLUSIONS

Scientific Conclusions

This study has provided an improved understanding of some of the materials handling properties of mechanically chipped materials. The following are the main conclusions that can be drawn from this investigation:

1. For water-saturated, noncohesive, uniformly-graded material, the angle of internal friction increases with a decrease in particle size.
2. For water-saturated, noncohesive, well-graded material, the angle of internal friction increases with a general increase in particle sizes.
3. A well-graded noncohesive material, from which size fractions are sieved out for testing, generally has a higher angle of internal friction than do individual size fractions.
4. Cell size does not appreciably affect the angle of internal friction so long as a proper maximum-particle-size-to-cell-size ratio ($\leq 1/6$) is maintained.
5. Saturated, cohesive materials (such as shales) have very low angles of internal friction, approaching zero as the proportion of small particles increases.

6. Dry well-grade cohesionless materials have an angle of internal friction very close to that of the same material saturated with water.
7. Dry well-graded cohesive materials have an angle of internal friction considerably higher than the same material saturated with water.
8. There is an indication that detergent solutions and rock softening solutions tend to decrease the angle of internal friction in noncohesive well-graded materials, the rock softening solutions having more of an effect than the detergent solutions.
9. Detergent and rock softening solutions do not affect the angle of internal friction for very cohesive materials containing small particles, since these angles are very close to 0° anyway.
10. Cutter head thrust and speed do appear to have a minor effect on the size consist of the muck, but geology and bit type used seem to have a greater effect on the size consist.

Practical Conclusions

In addition to the above conclusions, several direct applications to tunneling can be derived from these studies. Disc bits, as opposed to button inserts, are preferable for many tunneling applications. Although button bits have been found to be capable of boring through harder

rock than disc bits, the energy required to create fine muck is very high. Additionally, the handling of larger muck particles is easier than handling small particles. The piling of materials of larger consists on conveyers or in stockpiles would tend to result in more stable conditions at constant angles of piling than would the piling of material of smaller consists. Since the natural angle of repose would be higher for materials of larger consists than smaller (due to the higher angle of internal friction), more material could be stored in a smaller area.

Shaley or clayey materials seem to cause materials handling problems under most any conditions. Jamming at transfer points, sticking in tram cars, and degradation when stockpiled in the open subject to weather conditions are a few of the problems. It might be advantageous not to use a water spray when boring through such materials. This would simplify the handling of the muck from the face to the stockpile. Once stockpiled, however, humidity and rain would cause unstable conditions within the pile. Precautions in anticipation of slides must therefore be taken.

The use of alternative solutions for the spray would have an effect on the materials handling characteristics of the muck. Rock softeners will tend to lower ϕ and thereby slightly decrease piling efficiency. Once stockpiled

in the open, however, the effect of weather should dilute this saturation fluid, increase ϕ, and thereby increase the stability of the stockpile. Although rock hardeners were not used in tests, it is possible that they might increase ϕ. If this is the case, safe working conditions would require that consideration be given to the possibility of stockpile stability problems over a period of time, since rain and water would dilute the saturation fluid and decrease ϕ.

Finally, these studies might suggest one peripheral recommendation concerning slope stability along highway cuts and in dam fills. If a single size fill is to be used, the use of small noncohesive rock would seem to be the most effective. However, it appears that well-graded fill of fairly large size consist would be even more effective.

<u>Recommendations for Additional Research</u>

The conclusions of this investigation can be used to point out the need for further research. Below are listed a few areas of additional research that might be worth consideration:

1. Detailed examination of the effects of bit type and configuration on muck characteristics.

2. Optimization of the combined effects of energy consumed, advance rate and muck characteristics.

3. Applicability studies of large and small muck handling devices.

4. Continued studies of saturation fluid effects.

5. Muck characteristic tests in larger triaxial cells so that scalping of the large particles is not necessary.

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APPENDIX I

A DIARY OF SAMPLE COLLECTION

Metro Tunnel

Washington, D.C. trip, June 8, 1971

The investigators left State College about 7 a.m. for Washington, D.C., for the purpose of inspecting a tunnel site owned by the Washington Metropolitan Area Transit Authority. They arrived shortly after 11 a.m. and went first to the main Metro Building in L'Enfant Plaza. General aspects of the Metro were discussed with Mr. John Ansley, Assistant Director, Office of Construction.

The Metro is an extensive underground subway system, with its lines running radially from the center of town. Much of the system will be underground, with the parts in the suburbs above ground or in trenches. When completed, trains will be controlled from a central building, with only one company rider aboard each train for safety and emergencies. Scheduled completion date for the system is 1979.

After lunch, the investigators travelled to the Rock Creek tunnel which was being construc-ed in Rock Creek Park in northwest Washington They were given a tour of the tunnel by Mr. Lee True, resident engineer who was overseeing the work being done by S. A. Healy Company. The tunnel was about 750 feet long out of a total length of 4,000 feet. It was being advanced by conventional methods. The drilling and blasting scheme utilized a burn cut.

There were 103 holes drilled into the face, each hole being drilled to 10 feet, and pulling about 8 feet. Drilling took a little over an hour. There were a total of 13-drifter mounted drills, but only six-eight were used at a time. The tunnel operated on two shifts each day, averaging 75 feet of advance per week. Blasting was done once per shift. Mucking was done by one front-end loader and several LHD's. At the time of the visit, muck was loaded and carried immediately out of the tunnel. As the tunnel face advanced, muck was first moved out of the way of the drill face, and then picked up and moved out of the tunnel. No truck haulage was planned. Lining was done with shotcrete and was applied in three layers. The first layer was applied immediately, the second about 150 feet back from the working face, and the third sometime later. This entire 4,000 foot section of tunnel will terminate under Dupont Circle, where a station area 79 feet wide will be dug.

No sample was collected at this tunnel.

<u>Queen Lane Raw Water Conduit</u>

Philadelphia, Pa., June 24, 1971

On Thursday, June 24, 1971, samples of tunnelling machine cuttings were collected by the investigators. An one-quart mason jar sample was collected for percentage moisture determination, and approximately 60 lbs of cuttings were collected as a bulk sample.

Location of the tunnel portal is at Ridge Avenue and Schoolhouse Lane, Philadelphia. At the time of collection, the footage of tunnel advance was 4,100 feet. (Total length of tunnel will be 5,800 feet; the tunnel will connect to a vertical shaft.) The tunnel is circular, with an excavated diameter of 11 feet. Grade of the tunnel (in bound) is +1% for the first 3,000 feet, and +3% thereafter. The tunnel has several turns, corresponding to street location at the surface. Depth of cover is 50 to 105 feet. The purpose of the tunnel (to be concrete lined to 8 feet) is for raw water transfer from the Schuylkill River inland.

The rock type is a very micaceous Mica-Shist (Muscovite, Biotite, Phlogopite) with occasional lenses and stringers of fine-grained quartzite (less than 5 percent by volume Quartzite). The rock is friable and easily degraded; cuttings are 100 percent minus two inch and 90 percent minus six mesh, approximately. At the point where the sample was taken, the digging was reported to be easy (i.e., few or no quartzite stringers encountered). However, the presence of quartzite was reported to have no effect on the size consist of the cuttings. The samples were removed from the 18-inch width muck discharge conveyor of the tunnelling machine. One five feet long and and five inch deep continuous section of conveyor burden supplying the samples. The tunnelling machine was a

"Reed-Jarva Mark 14" machine. Tunnel constructors were S & M Construction Company, under contract to the city of Philadelphia.

<u>Lawrence Ave. Sewer Tunnel</u>

Chicago, Illinois, July 16, 1971

The investigators visited the Lawrence Avenue Sewer Tunnel at 2920 West Lawrence Avenue, in North Chicago. This job was being done by James McHugh Construction Company, S. A. Healy Company, and Kenney Construction Company. McHugh had the primary operating responsibility. The investigators spoke with Bob Cain and Bill Harriett. Bill took them underground. Bill Burton, the main foreman, was not on the job that day.

Chicago has a combined waste and storm sewer system. During heavy rains, the previous system was inadequate to handle the flow. The Lawrence Ave. Tunnel will act as a reservoir, holding the flow until the treatment plant can handle it. The tunnel was being bored in a very competent dolomitic limestone. This limestone is flat-lying, so rock bolting was advisable to strengthen the roof. Otherwise it was an excellent rock to bore. Entrance to the tunnel was by shaft to a depth of 255 feet. The tunnel was about 19,500 feet long, with about a half mile to go. When the tunnel is finished, the machine will be withdrawn up a shaft which was yet to be sunk at the far end of the tunnel.

If the shaft for some reason were not completed, the machine would have to be dismantled and backed out.

The machine being used was a Lawrence 007. The 007 was guided by a pilot borer, and was aligned by a laser on a target. This machine was brought in and first bored the 5,000 foot Hastings Road feeder tunnel. At the same time, the Lawrence Avenue Tunnel was being advanced 2,400 feet by conventional drill and blast methods. The mole was then brought into the main tunnel where it is now.

The drill-blast part of the tunnel is 19-1/2 feet high by 15-1/2 feet wide, which equals the volume of a 17 feet in diameter round hole. At one point there is a 500 foot radius curve, which was negotiated in order to follow Lawrence Avenue.

Muck came off a conveyor and was dumped into rail cars. It was at this point that the investigators did their sampling. Rail haulage was to the shaft, where the cars were pulled under a large hook, and were lifted off their dollies. The shaft is two-compartment; one compartment was a muck skip, and the other was the man cage. Muck was tripped from the skips into a large hopper, and then loaded into trucks. If trucks were late, the muck might be dumped into the ground and pushed onto an auxiliary pile until it could be moved later.

The investigators took a moisture sample and bulk sample from the end of the conveyor in the tunnel, and a bulk sample from the outside muck pile.

Strawberry Aqueduct, Layout Tunnel

Heber City, Utah, July 19, 1971

The tunnel site is located 40 miles east of Heber City, north of U.S. 40 on Currant Creek Road. It is part of the massive Central Utah Project. The purpose of the tunnel is to take water from Layout Creek and the proposed Currant Creek Reservoir and feed it into the Strawberry Reservoir, which is a water source to Salt Lake City and north central Utah. The Water Hollow Tunnel was complete, having been a joint effort of Gibbons and Reed and Boyles Brothers. Both the Layout and Currant tunnels had been contracted to S. A. Healy.

The investigators were on the site from 10 a.m. to 1:30 p.m. They spoke initially with Mr. Robert Ames. John Wagner, Chief Engineer for Healy, took them underground and answered their questions. The machine being used was a Robbins 141-127. It had a laser guide, which lasted 2-3,000 hours. The machine was also equipped with a shield. Muck was loaded into railway cars and hauled to a pile a short distance outside the portal. The cars were of the side-dump variety.

Muck movement in bad ground was inhibited by the high water content. Mud built up between the rollers and the conveyor, so instead of getting traction the rollers were spinning and the belt was barely moving. A moisture

sample was taken from the conveyor belt, and a bulk sample from the outside muck pile.

Navajo Irrigation Project

Farmington, New Mexico, July 21, 1971

The tunnel site is located about 16 miles east of Bloomfield, N.M. It is part of the Navajo Irrigation Project, a project to bring irrigation water to the Navajo Indian Reservation to the southwest. Two tunnels and a siphon were contracted to the Fluor Utah Company. At the time of the visit the tunnel was in 1,700 feet out of a total of 3.5 miles.

Questions about the project were answered by P. E. "Joe" Sperry. The investigators were taken underground by Jay Terry, Safety Engineer. The machine used was a Dresser with a 20 foot six inch head. It was a very spacious tunnel in terms of access to the machine. Besides the normal walkways along side of the mole, it had a full work deck situated atop the gantry. Trailing behind the mole was a 600-foot platform on rails, which was itself the rail switcher for the cars. This eliminated the need for a California switch elsewhere in the tunnel. The machine was laser aligned, visually sighted. Muck was handled by a conveyor and then dumped through a tipple in order to easily load the long (16 cubic yard) cars. The tipple was controlled by an operator who was watching it

on a closed-circuit television. Muck was taken out to a large pile, where it was spread by a front-end loader.

The tunnel was formerly in competent sandstone, which made it very dry since no water spray was used. At the time of the investigation the tunnel was in a lense of weak, wet shale. The operation was down awaiting shotcrete equipment. This was to be placed on the upper work deck, in hopes of containing the bad ground without having to go to steel ribs. Because it was down, no moisture sample was taken. The bulk sample was taken from the outside muck pile which consisted of very friable material.

<u>Fryingpan Project, Nast Tunnel</u>

Meredith, Colorado, July 22, 1971

The tunnel site is about eight miles east of Thomasville, Colorado, very near the Continental Divide at about 10,000 feet above sea level. The investigators were taken into the tunnel by Wilbert Steele, Safety Engineer. The tunnel is part of the major Fryingpan-Arkansas Project, which is to divert water from the Fryingpan drainage basin east across the Continental Divide into the Arkansas River, where it will eventually go to Colorado Springs and eastern Colorado. Only water above 10,000 feet may be taken from the Fryingpan basin. Below that it will be left to drain into the Fryingpan River and Ruedi Reservoir. Peter Kiewit Sons had the contract on the Nast Tunnel.

Mucking was by conveyor belt mounted on a muck master which was supported by frames on the track. These frames were movable, so when the train came in, the frames were pushed back behind the train, and the conveyor was supported atop the cars. Muck was dumped and spread on the surface by a front end loader. The muck was later used as road material for their access roads. A moisture sample was taken from a settling pond, and a bulk sample from right alongside the pond.

Climax Molybdenum Mine

Climax, Colorado, July 23, 1971

The investigators spent almost a full day at Climax. The people there were extremely helpful. The investigators spoke above ground with Bob Elder, head of Industrial Engineering. Mike Gibson, a mechanical engineer, took them underground. Climax had had a Calweld machine, but had given up on it. It had bored a 1,000 foot drift, when the gauge cutters failed. They were replaced, and within 10 feet were destroyed again. Climax and Calweld then mutually terminated their contract.

The first drift was in porphyry of 15-18,000 psi compressive strength. The later drift was in rock of an average 20,000 psi compressive strength. The first drift was 13 feet in diameter, the major problems being in materials handling. The machine produced spalls, which

jammed in hoppers and tore belts. The grippers had trouble in soft ground. Often fracture resulted at the points where the grippers had been when they were removed. Scrapers and scoops at the face wore rapidly, which produced large cutter wear. Almost every day the scrapers had to be built up. Finally Calweld came out with a spring-loaded scraper which worked better. The cutters on the machine were button roller.

The muck was very fine and slushy, so it hung up in skips and shafts, making handling very difficult. The muck collected on the floor 18-30 inches thick, which ultimately had to be mucked out by front end loader. This took four months. Cost of the initial moling was three times normal conventional costs. One bright spot was support which only cost half as much as conventional methods. The strongest supports used were four inch I beams on five foot centers, full circle, with 3 x 12 foot lagging. Most of the support, however, consisted of random rock bolting. Some ground was even unsupported. Future maintenance of the drift will also be cheaper than conventional ones. Handling track and equipment was by a monorail alongwide the machine. Mucking was by six-car train. No sample was taken.

White Pire Copper

White Pine, Michigan, July 26, 1971

White Pine Copper Mine is located on Route 64, White Pine, in the upper Michigan peninsula just south of Lake Superior. The investigators spent most of the day with Cliff Hanninen and Jerry Bennett, of Mine Research. They also spoke for a short time with Joe Patrick, a Vice President; and Bill Lane, Bore Supervisor.

The tunneling machine, a Robbins, was boring a two-mile ventilation and electrical tunnel. The tunnel was 110 feet under the ore syncline, so it was going down, and eventually came back up an average of a 10 percent grade. It had bored on as much as a 20 percent downgrade. Boring was in sandstone, 25,000 psi, 60 percent silica content. The machine used disc cutters and was getting quite large breakage pieces. The tunnel will connect the eastern shaft with the main mine. There was to have been a travelway above the tunnel in the orebody. Every 1,000 feet or so a raise was to be bored to the travelway for ventilation. Also, the machine tunnel gives good access for testing the orebody.

This tunnel was the most efficient observed. It had the best looking muck, best costs, and best materials handling. A conveyor belt was used all the way from the machine to the shaft. White Pine has a large rock mechanics section, and runs extensive tests on samples. They

have been mining since 1955, and have a large orebody, averaging 1.4 percent CuS_2. The investigators took no moisture sample, because the machine was down for cutter change. A bulk sample was collected from an outside muck pile.

Mid-Toronto Interceptor Sewer

Toronto, Ontario, July 27, 1971

The tunnel site visited was located at 500 Gerrard Street, although the tunnel runs about 2-1/2 miles through east Toronto. The investigators spoke to John MacKay, who was good enough to come out at 7:30 p.m. to show them around. The purpose of the tunnel is to collect sewage and water from East Toronto, and to hold it until the treatment plant on Lake Ontario can handle it. The sewage system in Toronto, like in Chicago, is a combined storm and waste system.

While the investigators were there, the machine was down. It had bored about 2-1/2 miles, and then an area was dug by cut and fill. At the time the investigators were there, the machine was being lowered down a shaft to complete about 2,000 feet of tunnel. The machine had to be broken into only two pieces to be lowered. The maximum depth of the tunnel is 90 feet, with minimum depth of 30 feet under the river. Concreting was done over a length of 150 feet (five forms of 30 feet each). Eventually

the whole tunnel was lined. Mucking was by rail. The biggest problem was materials handling, as the contractor could not handle the muck as fast as the muck came off the face. MacKay claimed they had had no trouble with the grippers breaking the wall rock.

<u>Navajo Irrigation Project</u>

Farmington, New Mexico, July 5, 1972

The details of the tunnel information and machine setup are given in the July 21, 1971 diary. Once again, questions were answered by Mr. P. E. "Joe" Sperry. Mr. Sperry said that the investigators had arrived just in time, since the machine was going to be holing through in the next day or two. The investigators were taken underground by Mr. Jay Terry, the safety engineer, and Mr. Chuck Prior, the foreman. They cooperated completely, varying machine parameters just as asked.

The investigators had ten army surplus ammunition boxes with them, so they filled two boxes for each of the five samples taken. The first sample taken was at normal cutter head thrust and RPM. For the second and third samples, RPM was maintained and thrust was reduced. For the fourth and fifth samples, the thrust was brought back to normal and the RPM was reduced. The thrust and RPM for the five samples is shown in Table 2, Chapter 4.

Mr. Prior explained that at greater than eight RPM, centrifugal force prevents muck from falling on the conveyor belt readily. This causes re-cycling and re-grinding of the muck, which is undesirable. Consequently, no samples were taken at an RPM greater than eight. Additionally, the machine was operating on only three of its four thrust cylinders during our visit. One million, ninety thousand pounds was, therefore, the maximum thrust that could be achieved for a sample.

With the cooperation of Mr. Sperry, Mr. Terry, and Mr. Prior, all of the samples were collected within 45 minutes. The samples were shipped to State College via REA.

Fryingpan Project, Nast Tunnel

Aspen, Colorado, July 7, 1972

Upon arriving at the office of Peter Kiewit Sons, the investigators were informed by Mr. Norm Tennock that the machine was down and would not be operating again for quite awhile. The machine was in a fault zone and had been damaged by boulders falling into the tunnel. The situation was so bad that it was decided to drill and shoot from an access adit back to the machine. The machine would then be walked up the tunnel to the face, and tunneling by mole would continue.

Button bits had been used on the mole, but plans were to go to a disc type bit with button inserts. Upon driving up to the tunnel site, the investigators understood why button bits were being done away with. The muck on the stockpile was very fine and wet. Disc cutters would help to generate larger particles and perhaps save on energy and re-grinding. Due to the situation at Nast, no new samples could be taken.

White Pine Copper

White Pine, Michigan, July 10, 1972

The first personal contact at White Pine was with Mr. A. C. Bigley, Jr., Head of Metallurgical Research, since Dr. Cliff Hanninen of Mine Research was not in. Once again, the investigators were told that the machine was down. The Robbins machine had been negotiating a curve and had reached a point beyond which the conveyor belt could no longer be used. A connection tunnel at this curve was being mined by drill and shoot. This connection tunnel would take care of the conveyor belt problem in addition to providing better ventilation. A two-hundred pound sample of the muck (the Nonesuch shale) was taken at the outside stockpile, however.

The next day, the investigators met Bert Caverson of the Rock Mechanics section. Mr. Caverson introduced them to one of his technicians who took them on a tour of the

mine and showed them the Atlas-Copco machine, White Pine's second tunneling machine. The machine was explained to them by Clark Slay, who seemed very pleased with the operation and 700-feet-per-month advance rate of the machine. The only serious problem with the Atlas-Copco seems to be a materials handling one.

After visiting other parts of the mine, the investigators were taken to the surface, and departed. The sample was brought back to State College by automobile.

Moss Point Drainage System

This tunnel system is owned by the City of Euclid, Ohio (just north of Cleveland), and was being bored by S & M Constructors. The system consists of several connecting tunnels, two of which were being bored by two Jarva machines. When completed, the system will drain storm water from the Cleveland area, outletting into Lake Erie.

One of the machines was an 18-foot mixed-face borer, and the other was a 14-foot three inch hard-rock tunneler. The mixed-face borer was expected to encounter silty sediments as it neared Lake Erie, whereas the hard-rock tunneler was to remain in shale. Both machines were operating at a depth of approximately 60 feet. The muck from both machines was transported to the junction of the tunnels by trains. At the junction, which was open to the surface, a crane lifted the hoppers of the cars out of the

tunnel and dumped them onto the ground. A front-end loader filled waiting trucks with the muck which was then hauled away.

Since only one machine was a hard-rock tunneler, the investigators took a sample of approximately 150 pounds from that machine alone. The sample consisted of a very weak shale.

North Branch Intercepter Sewer

New York City, December 28, 1972

Larry Beck and Don Raab left State College by 2-1/2-ton truck at 6:00 a.m. and arrived in Fort Lee, New Jersey at 12:00 p.m. By 1:30 p.m. they were at the tunnel site talking with Mr. Bruno Deitl, Superintendent.

The 11-feet in diameter Jarva machine dumped the muck onto an 18-inch conveyor belt which dumped into a hopper feeding another 18-inch conveyor that was 120 feet long. This belt fed into 17 cubic-yard (20 feet long) railroad cars which entered and left the tunnel three at a time. These cars were pulled by 10-ton locomotives. There was no facility for the trains to pass each other inside this tunnel. The cars were taken to the shaft entrance of the tunnel and then were lifted out by a crane one at a time, and dumped.

Mr. Deitl did not want visitors to go underground. Maneuvering sample collecting equipment through the small

openings in the 11-foot tunnel would have been too difficult. Consequently, one 100-pound sample was taken from a fairly representative pile in a railroad car, and another 1,000 pounds of sample were taken from the stockpile outside.

APPENDIX II

ASSEMBLED DATA SHEETS

Table 6. Philadelphia Tunnel Data

Date of Visit:	June 24, 1971
Location:	Philadelphia - Ridge Ave. & Schoolhouse Lane
Owner of Tunnel:	City of Philadelphia
Drilling Contractor:	S & M Contractors
Person in Contact with:	Ron A. Marra
Name of Tunnel:	Queen Lane Raw Water Conduit
Diameter:	11 feet O.D. lined to 8 feet
Length to Date:	4,100 feet out of 5,800 feet
Best Shift:	40 feet
Best Day:	89 feet
No. of Men in Tunnel:	4 men plus locomotive operator
Machine Name and No.:	Jarva Mark 14
Horsepower:	4 at 125 hp each
Type of Cutters:	Disc kerf w/gauge teeth. 27 Total
Rotation Speed:	10 RPM
Thrust Against Face:	1,200,000 pounds maximum
Thrust Cylinder Diameter:	4-1/4 inch. 8 cylinders
Water Spray:	Yes Amount: 5 GPM Type: Pure water
Rate of Advance:	About 10 feet per hour
Size of Conveyor Belt:	18 inches
Approximate Sample Weight:	75 pounds
Present Type of Rock:	Mica Schist (predominately biotite, some muscovite, with quartz bands)
Compressive Strength:	15,000 to 35,000 psi
Other Comments:	Laser aligned-spectra physics, 55-105 feet of cover, little overbreak. Sampled from conveyor belt

Table 7. Chicago Tunnel Data

Date of Visit:	July 16, 1971
Location:	2920 W. Lawrence Ave., Chicago
Owner of Tunnel:	City of Chicago
Drilling Contractor:	James McHugh (also S. A. Healy)
Person in Contact with:	Bob Cain, Bill Harriett
Name of Tunnel:	Lawrence Ave. Sewer Tunnel
Diameter:	13 feet 8 inches
Length to Date:	19,500 feet, 1/2 mile to go
Best Shift:	49.4 feet (long shift)
Best Day:	111.3 feet
No. of Men in Tunnel:	3 machine operators and 4 laborers
Machine Name and No:	Lawrence 007
Horsepower:	3 at 250 hp for main drive
Type of Cutters:	27 disc with button inserts
Rotation Speed:	9 RPM (Pilot = 30 RPM)
Thrust Against Face:	Max = 1,500,000 pounds
Thrust Cylinder Diameter:	?
Water Spray:	No
Rate of Advance:	20 feet per shift, 60 feet per day
Size of Conveyor Belt:	24 inches
Approximate Sample Weight:	150 pounds
Present Type of Rock:	Dolomitic limestone
Compressive Strength:	16,000-23,000 psi
Other Comments:	Large chamber 19-1/2 feet high x 15-1/2 feet = volume of 17 feet in diameter. Sampled from conveyor belt

Table 8. Heber City Tunnel Data

Date of Visit: July 19, 1971

Location: 40 mi east of Heber City in Currant Creek Rd.

Owner of Tunnel: Bureau of Reclamation

Drilling Contractor: S. A. Healy

Person in Contact with: Robert Ames, John Wagner

Name of Tunnel: Layout Tunnel Strawberry Aqueduct

Diameter: 12 feet 11 inches concrete lined to 10 feet 4 inches

Length to Date: 1,200 feet out of 17,355 feet

Best Shift: 67 feet

Best Day: 170 feet

No. of Men in Tunnel: 6 optimum but up to 15 in bad ground

Machine Name and No.: Robbins 141-127

Horsepower: 600 hp

Type of Cutters: 29 Disc

Rotation Speed: Variable 3 or 6

Thrust Against Face: Up to 750,000 pounds

Thrust Cylinder Diameter: 4 at 9 inches each

Water Spray: Yes Amount: 2-3 GPM Type: Pure water

Rate of Advance: ?

Size of Conveyor Belt: 30 inches

Approximate Sample Weight: 100 pounds

Present Type of Rock: Sandstone

Compressive Strength: ?

Other Comments: Sample from outside due to present bad ground in tunnel. Sampled from stock pile

Table 9. Farmington Tunnel Data

Date of Visit:	July 21, 1971
Location:	16 miles south of Bloomfield, New Mexico
Owner of Tunnel:	Bureau of Reclamation
Drilling Contractor:	Fluor Utah
Person in Contact with:	Joe Sperry, Jay Terry
Name of Tunnel:	Navajo Irrigation Project #3
Diameter:	20 feet 6 inches lined to 18 feet
Length to Date:	1,700 feet out of 3.5 miles
Best Shift:	65 feet
Best Day:	178 feet
No. of Men in Tunnel:	12
Machine Name and No.:	Dresser
Horsepower:	700 hp D.C.
Type of Cutters:	36 double disc or button insert
Rotation Speed:	6 RPM (variable 2-10)
Thrust Against Face:	850,000 pounds
Thrust Cylinder Diameter:	4 at 11 inches each
Water Spray:	No
Rate of Advance:	3 inches per minute, 15 feet per hour
Size of Conveyor Belt:	30 inches
Approximate Sample Weight:	80=90 pounds
Present Type of Rock:	Sandstone
Compressive Strength:	3,000 psi for sandstone
Other Comments:	Sandstone sample from outside muck pile. Sampled from stock pile

Table 10. Nast Tunnel Data

Date of Visit:	July 22, 1971
Location:	8 miles east of Meredith, Colorado
Owner of Tunnel:	Bureau of Reclamation
Drilling Contractor:	Peter Kiewit Sons
Person in Contact with:	Wilbert Steele
Name of Tunnel:	Nast
Diameter:	10 feet, lined only in bad ground
Length to Date:	2,800 feet out of 16,800 feet
Best Shift:	40 feet
Best Day:	60 feet
No. of Men in Tunnel:	8
Machine Name and No.:	Wirth
Horsepower:	600 hp
Type of Cutters:	26 button rollers
Rotation Speed:	8 RPM
Thrust Against Face:	1,600 psi
Thrust Cylinder Diameter:	?
Water Spray:	Yes Amount: 26 GPM Type: Pure water
Rate of Advance:	?
Size of Conveyor Belt:	24 inches
Approximate Sample Weight:	80 pounds
Present Type of Rock:	Granite
Compressive Strength:	30,000 psi (guess)
Other Comments:	Machine down, so most recent muck mined 4 hours previously sampled. Sampled from stock pile

Table 11. White Pine Copper Tunnel Data

Date of Visit: July 26, 1971
Location: Rt. 64, White Pine, Michigan
Owner of Tunnel: White Pine Copper Company
Drilling Contractor: White Pine Copper Company
Person in Contact with: Cliff Hanninen, Bill Lane, Joe Patrick
Name of Tunnel: No name
Diameter: 18 feet 2 inches
Length to Date: 4,800 feet out of 2 miles
Best Shift: 24 feet in 8 hours
Best Day: 44 feet in 2 shifts
No. of Men in Tunnel: 6 in boring shift, 8 in maintenance
Machine Name and No.: Robbins 181-122
Horsepower: 800 hp
Type of Cutters: 47 disc plus 1 center tri-disc
Rotation Speed: 4-1/2 RPM
Thrust Against Face: 1,200,000 pounds
Thrust Cylinder Diameter: 4 at 12 inches
Water Spray: Yes Amount: 15 GPM Type: Pure water
Rate of Advance: 4 feet per hour, 18 feet per day, 360 feet per year
Size of Conveyor Belt: 30 inches on machine, 36 inches in main line
Approximate Sample Weight: 80 pounds
Present Type of Rock: Sandstone
Compressive Strength: Up to 25,000 psi
Other Comments: Driving down a 10 percent dip. Sampled from stock pile

Table 12. Toronto Tunnel Data

Date of Visit: July 27, 1971

Location: 500 Gerrard Street, Toronto

Owner of Tunnel: City of Toronto

Drilling Contractor: S. McNally & Sons

Person in Contact with: John McKay

Name of Tunnel: Mid-Toronto Intercepter Sewer

Diameter: 12 feet lined to 10 feet

Length of Date: 2-1/2 miles with 2,000 feet to go.

Best Shift: "

Best Day: ?

No. of Men in Tunnel: ?

Machine Name and No.: Robbins 126

Horsepower: 600 hp

Type of Cutters: 25-30 disc

Rotation Speed: 5-10 RPM

Thrust Against Face: ?

Thrust Cylinder Diameter: ?

Water Spray: ?

Rate of Advance: ?

Size of Conveyor Belt: ?

Approximate Sample Weight: 80 pounds

Present Type of Rock: Shale

Compressive Strength: 5,000 psi

Other Comments: Sample from outside muck pile. Sampled from stock pile

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Table 13. Farmington Tunnel Data

Date of Visit:	July 5, 1972
Location:	16 miles south of Bloomfield, New Mexico
Owner of Tunnel:	Bureau of Reclamation
Drilling Contractor:	Fluor Utah
Person in Contact with:	Joe Sperry, Jay Terry
Name of Tunnel:	Navajo Irrigation Project #3
Diameter:	20 feet 6 inches lined to 18 feet
Length to Date:	3.4 miles out of 3.5 miles
Best Shift:	about 100 feet
Best Day:	247 feet, best week - 1066 feet
No. of Men in Tunnel:	12
Machine Name and No.:	Dresser
Horsepower:	700 hp D.C.
Type of Cutters:	36 double disc
Rotation Speed:	5-8 RPM
Thrust Against Face:	612,000-1,090,000 pounds
Thrust Cylinder Diameter:	4 at 11 inches each
Water Spray:	No
Rate of Advance:	3 inches per minute - 15 feet per hour
Size of Conveyor Belt:	30 inches
Approximate Sample Weight:	1,100 pounds
Present Type of Rock:	Sandstone with shale bands
Compressive Strength:	Very weak
Other Comments:	Five samples were taken at various thrusts and RPM. Sampled from conveyor belt

Table 14. White Pine Tunnel Data

Date of Visit:	July 10, 1972
Location:	Rt. 64, White Pine, Michigan
Owner of Tunnel:	White Pine Copper Company
Drilling Contractor:	White Pine Copper Company
Person in Contact with:	Cliff Hanninen, Jack Sipola
Name of Tunnel:	No name
Diameter:	18 feet 2 inches
Length to Date:	7,000 feet out of 2 miles
Best Shift:	24 feet
Best Day:	44 feet
No. of Men in Tunnel:	6
Machine Name and No.:	Robbins 181-122
Horsepower:	800 hp
Type of Cutters:	47 disc plus 1 center tri-disc
Rotation Speed:	4-1/2 RPM
Thrust Against Face:	1,250,000 pounds
Thrust Cylinder Diameter:	4 at 12 inches
Water Spray:	Yes Amount: ? Type: Pure water
Rate of Advance:	5-1/2 feet per hour
Size of Conveyor Belt:	30 inches on machine, 36 inches on main line
Approximate Sample Weight:	100 pounds
Present Type of Rock:	Nonesuch Shale
Compressive Strength:	?
Other Comments:	Sampled from stock pile

Table 15. Cleveland Tunnel Data

Date of Visit: September 14, 1972

Location: Euclid, Ohio

Owner of Tunnel: City of Euclid

Drilling Contractor: S & M Constructors

Person in Contact with: Ed Norman, Dick Stier

Name of Tunnel: Moss Point Drainage System

Diameter: 14 feet 3 inches

Length to Date: 1,976 feet out of 3,800 feet

Best Shift: 30 feet

Best Day: 77 feet, 272 feet for 5 days

No. of Men in Tunnel: 12

Machine Name and No.: Jarva Mark 12-1403

Horsepower: 500 hp

Type of Cutters: Reed QK multiple disc

Rotation Speed: 10.75 RPM

Thrust Against Face: 1,134,000 pounds

Thrust Cylinder Diameter: ?

Water Spray: Yes Amount: 5 GPM Type: Pure water

Rate of Advance: 12 feet per hour

Size of Conveyor Belt: 24 inch on machine, 18 inch trailing

Approximate Sample Weight: 175 pounds

Present Type of Rock: Shale

Compressive Strength: 1,500-2,000 psi

Other Comments: Sampled from conveyor belt

Table 16. New York Tunnel Data

Date of Visit: December 28, 1972
Location: George Washington Bridge, New York City
Owner of Tunnel: City Environmental Protection Administration
Drilling Contractor: Perini
Person in Contact with: Bruno Deitl
Name of Tunnel: North Branch Interceptor Sewer Conduit
Diameter: 11 feet
Length to Date: 7,500 feet out of 10,000 feet
Best Shift: 40 feet
Best Day: 96 feet
No. of Men in Tunnel: 15-16
Machine Name and No.: Jarva Mark 12
Horsepower: 500 hp
Type of Cutters: Reed carbide insert on steel disc
Rotation Speed: 9.8 RPM
Thrust Against Face: 1,000,000 pounds
Thrust Cylinder Diameter: 6-8 inches
Water Spray: Yes Amount: ? Type: Pure water
Rate of Advance: 2-10 feet per hour
Size of Conveyor Belt: 18 inches
Approximate Sample Weight: 1,200 pounds
Present Type of Rock: Manhattan mica schist (biotite)
Compressive Strength: 10,000-30,000 psi
Other Comments: Sampled from railroad car

APPENDIX III

GRADATION FOR EACH SAMPLE

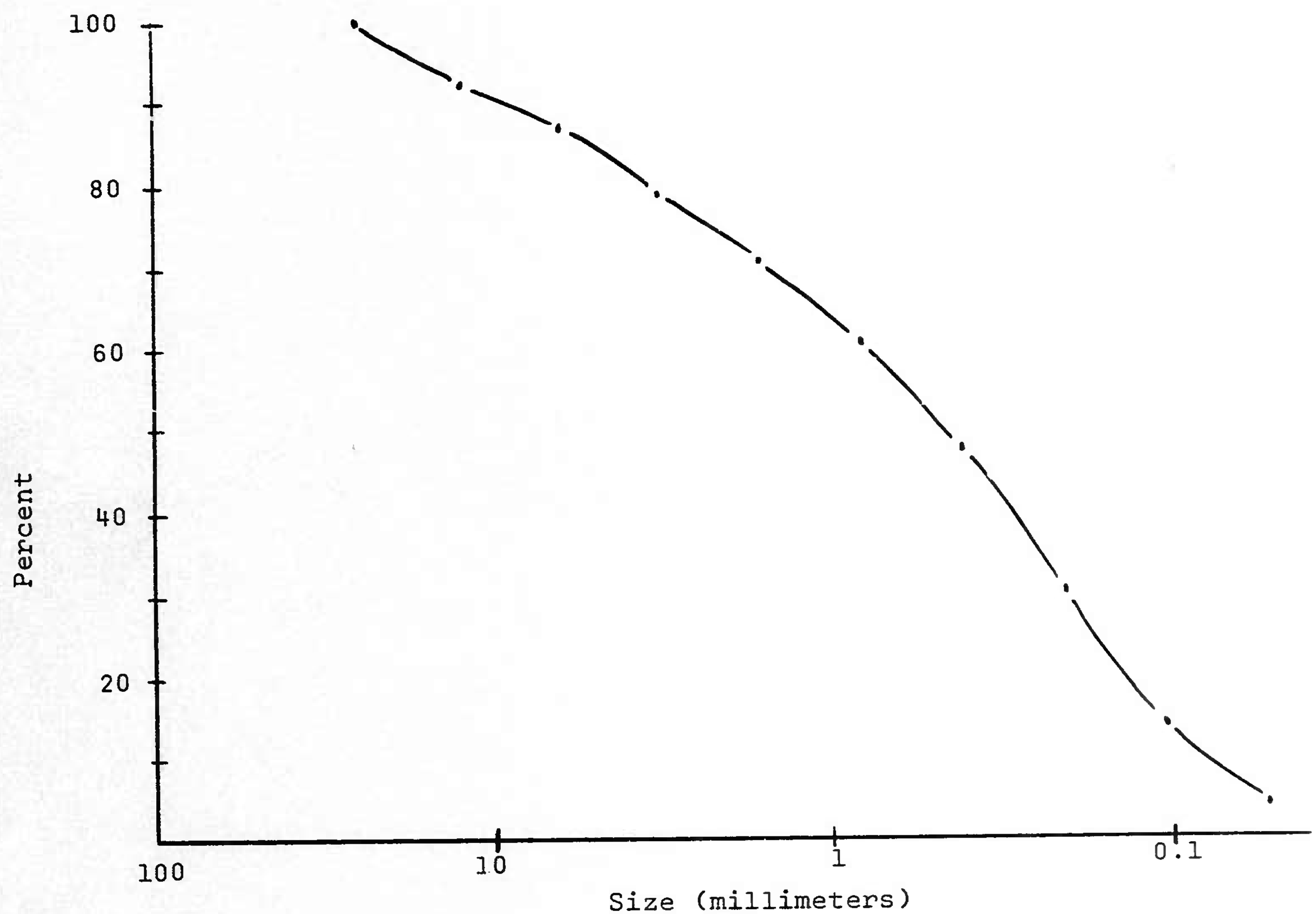

Figure 11. Phildelphia Tunnel

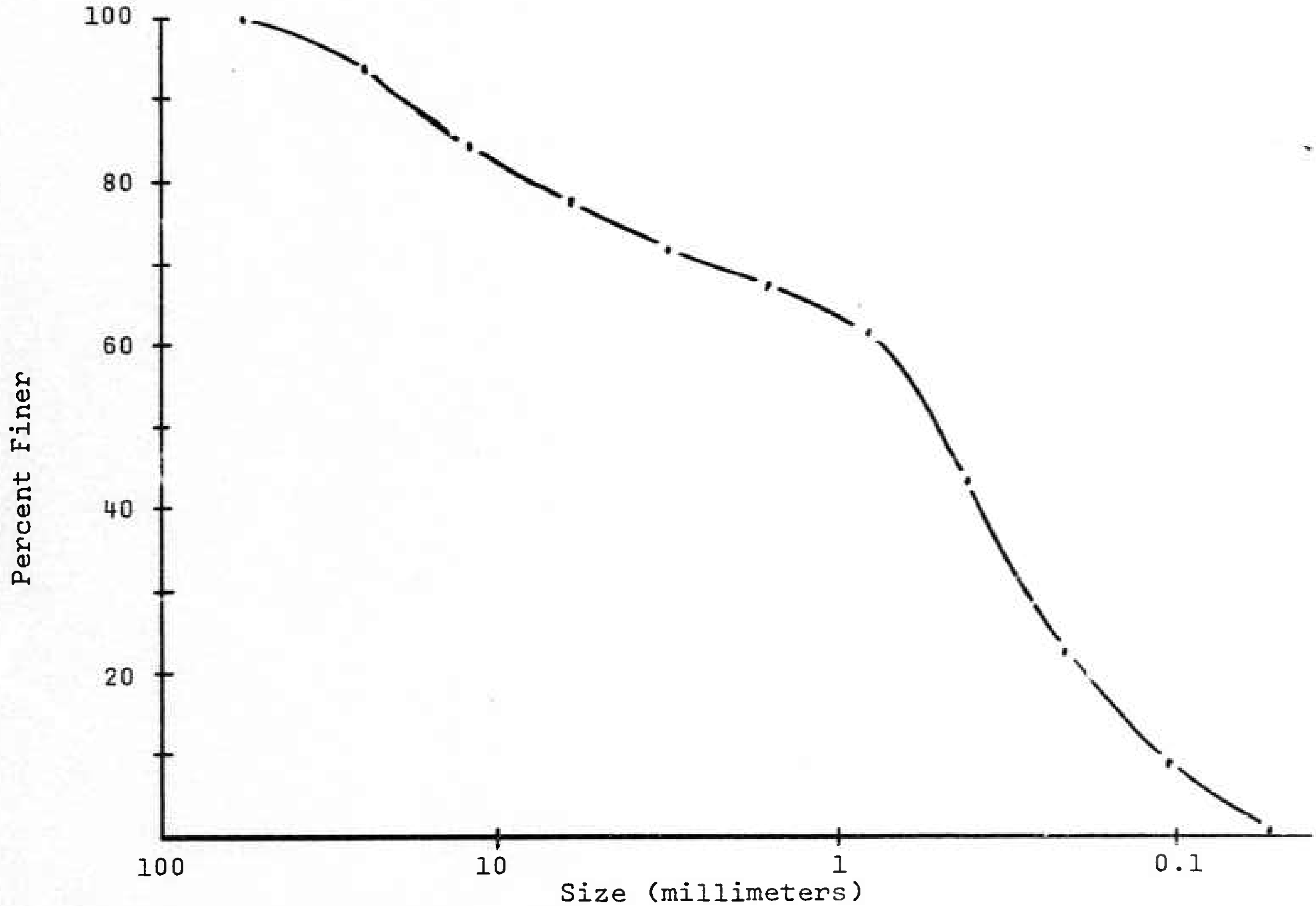

Figure 12. Farmington (1971) Tunnel

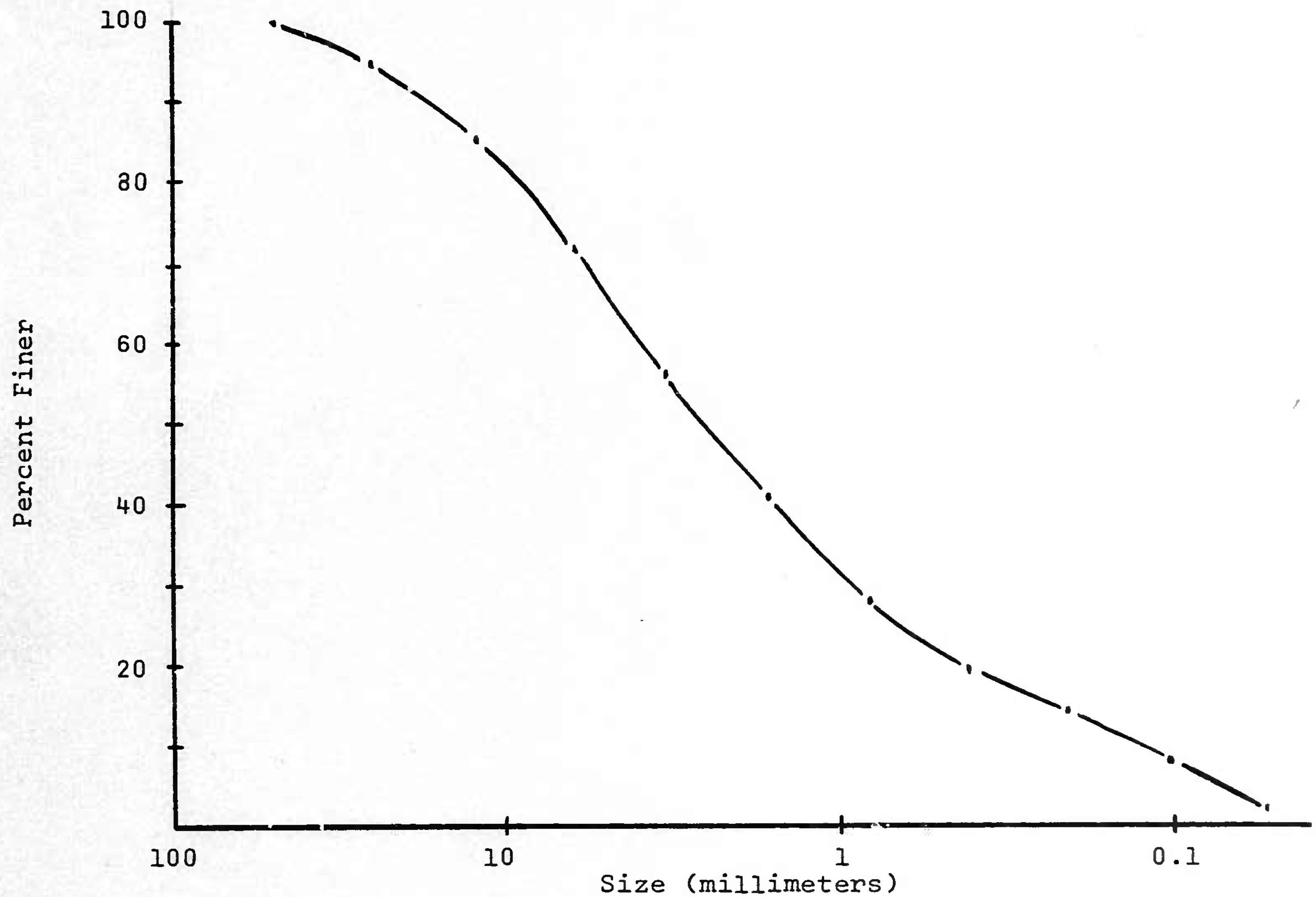

Figure 13. Heber City Tunnel

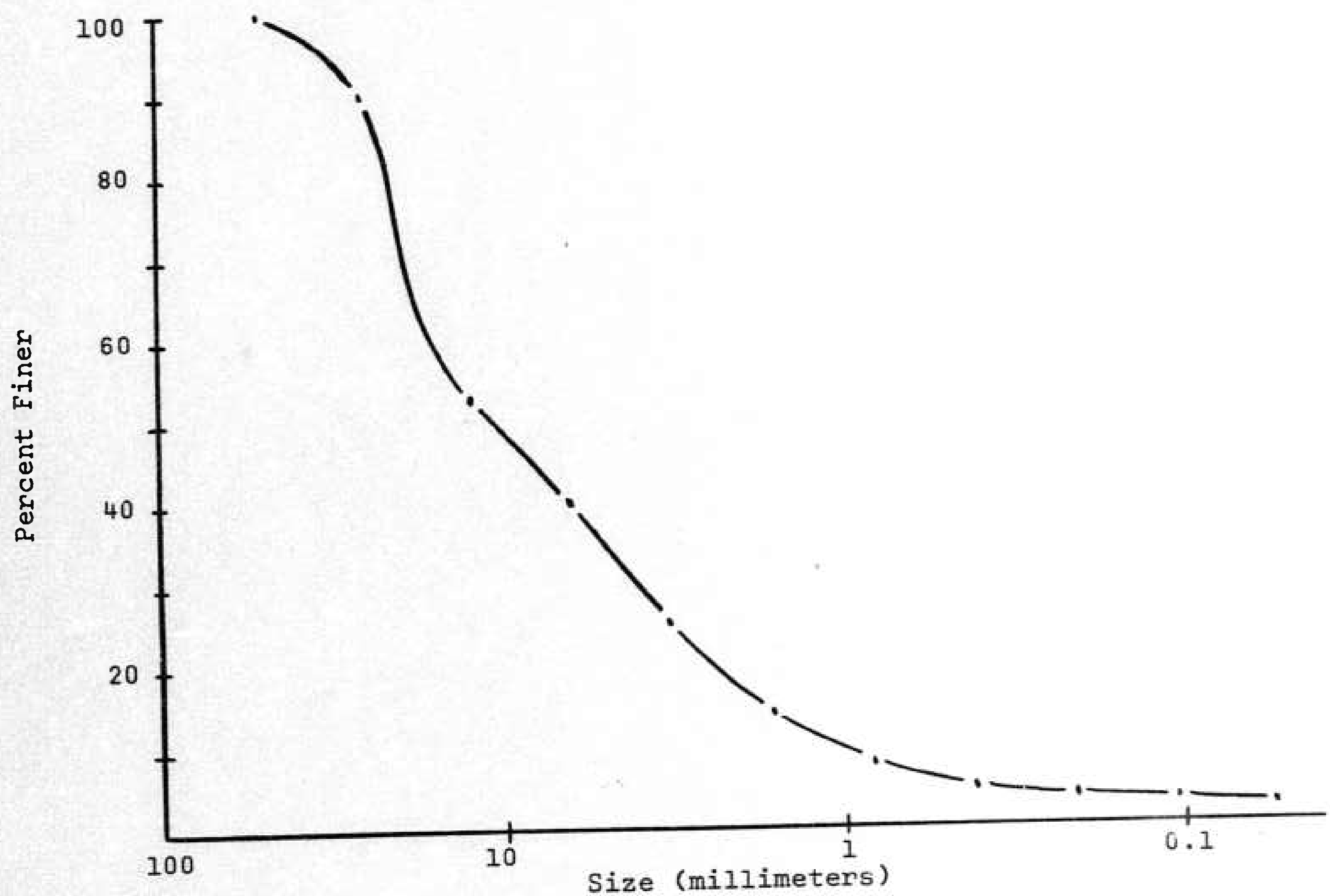

Figure 14. Toronto Tunnel

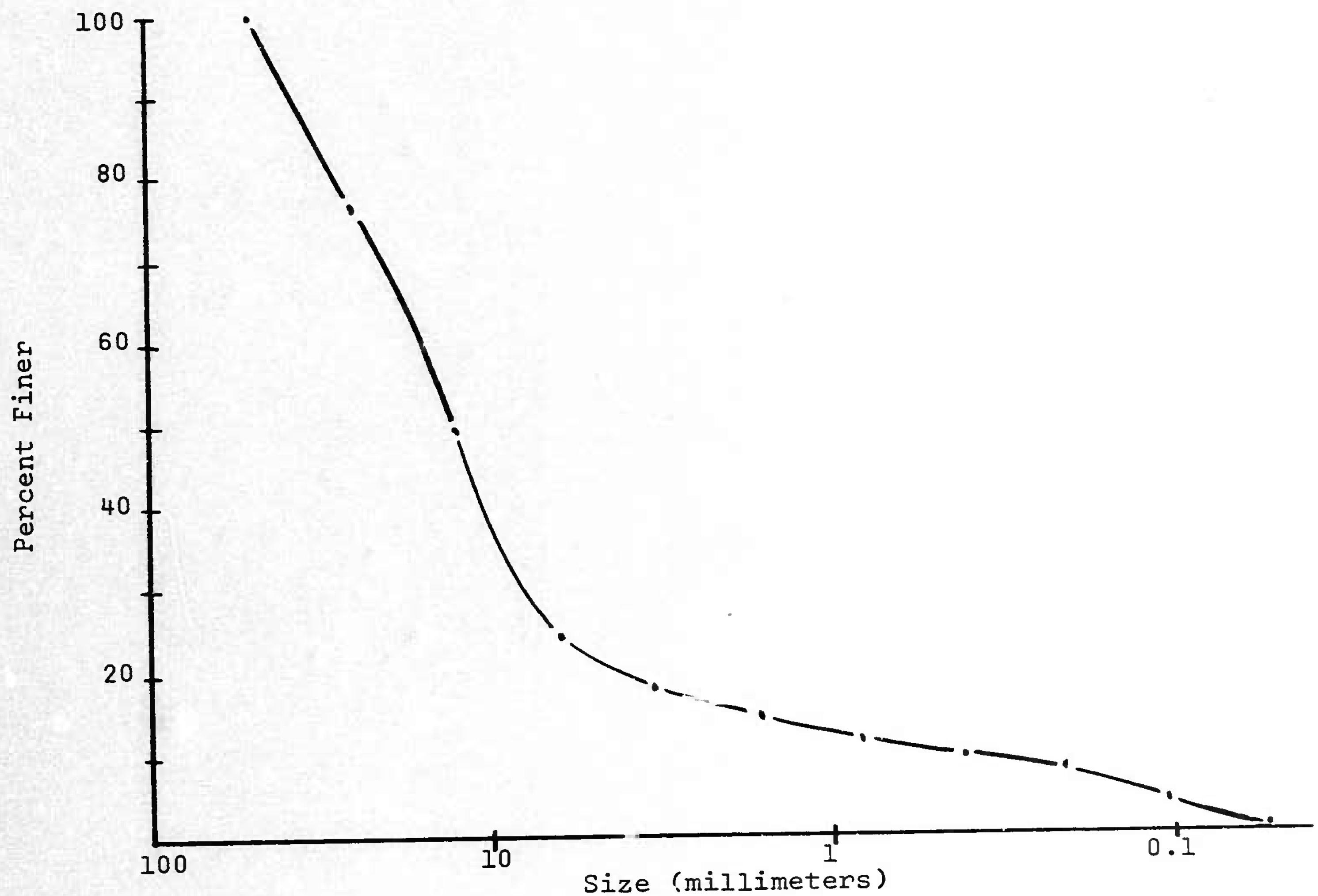

Figure 15. White Pine (1971) Tunnel

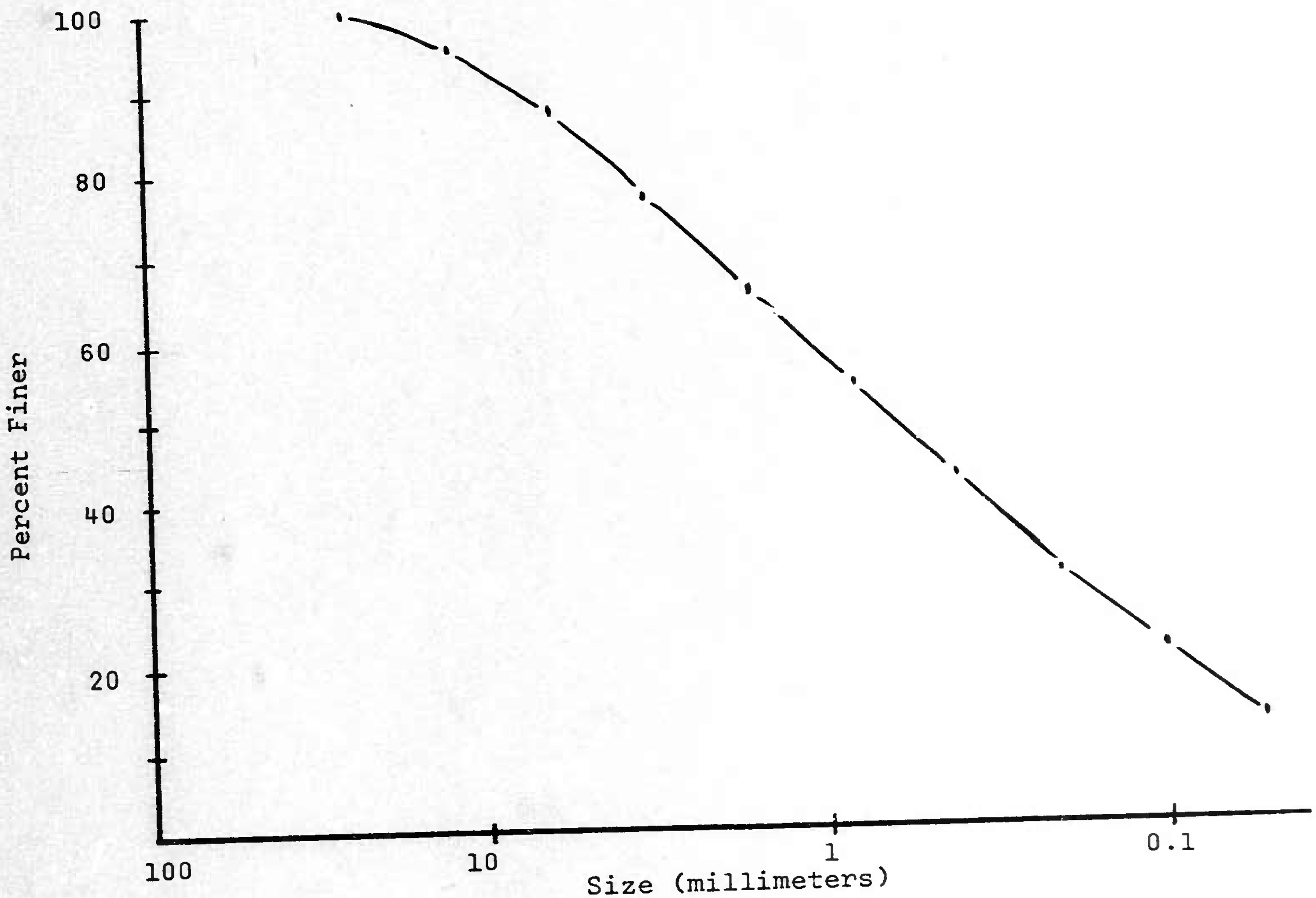

Figure 16. Nast Tunnel

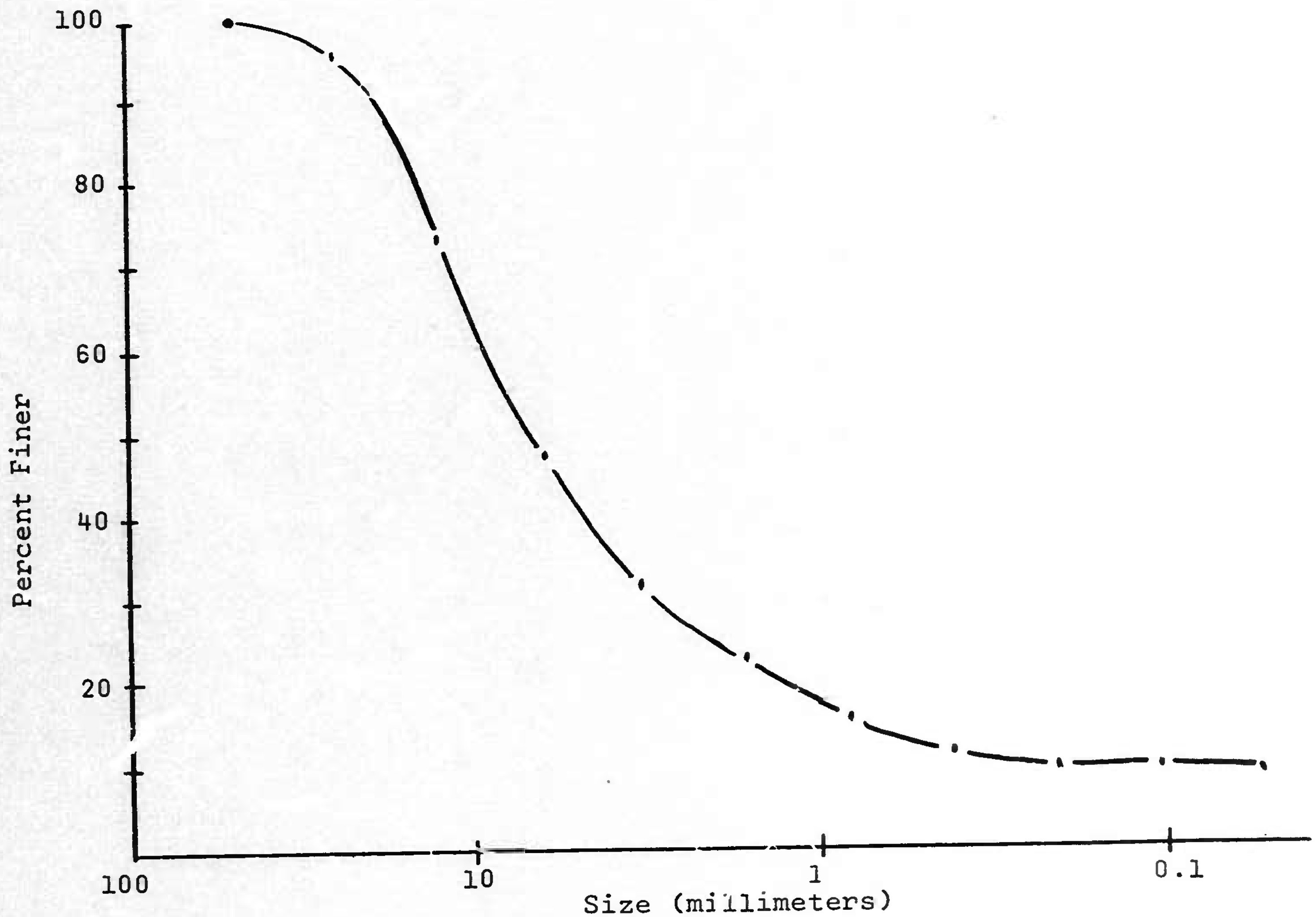

Figure 17. Chicago Tunnel

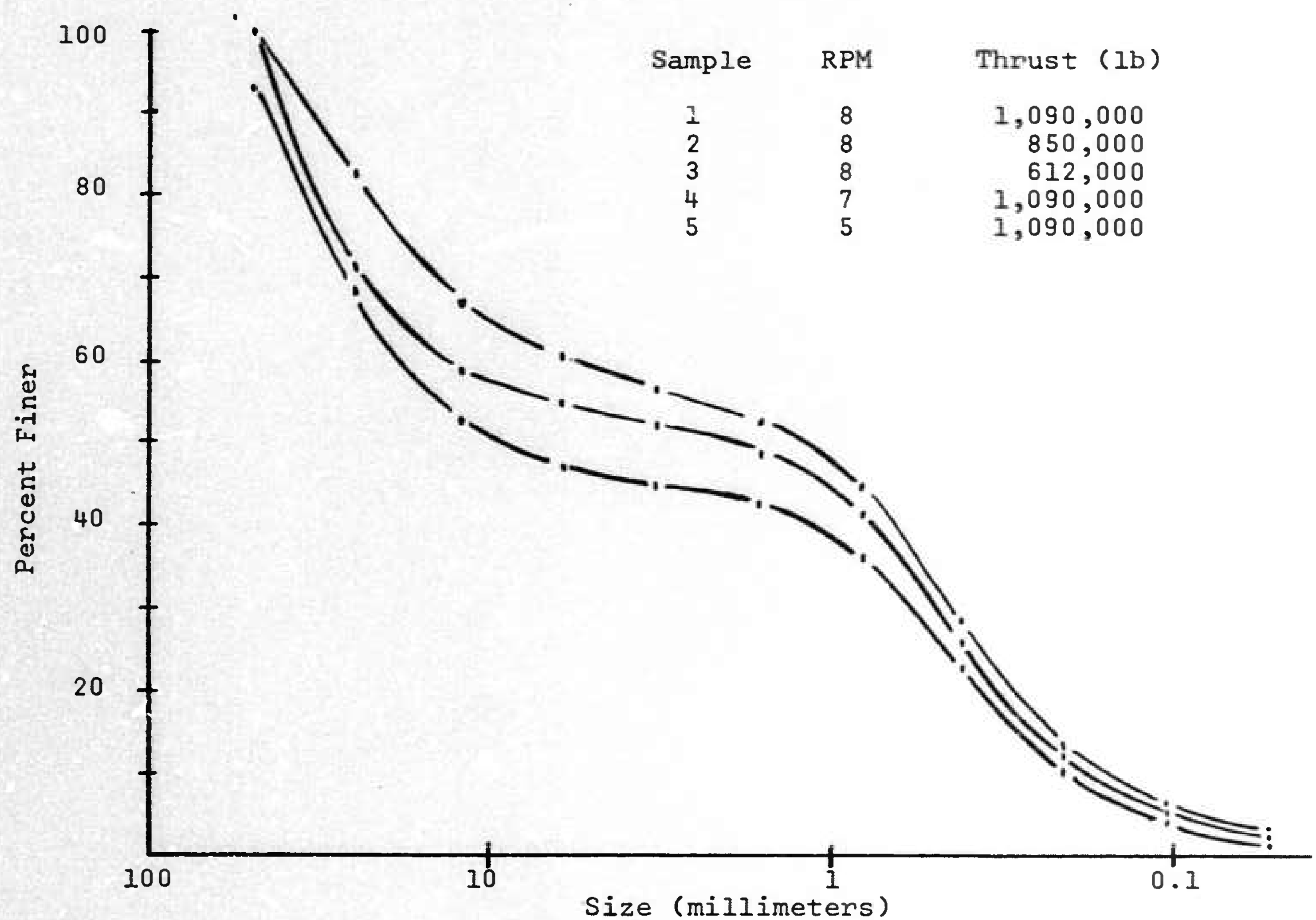

Figure 18. Farmington (1972) Tunnel

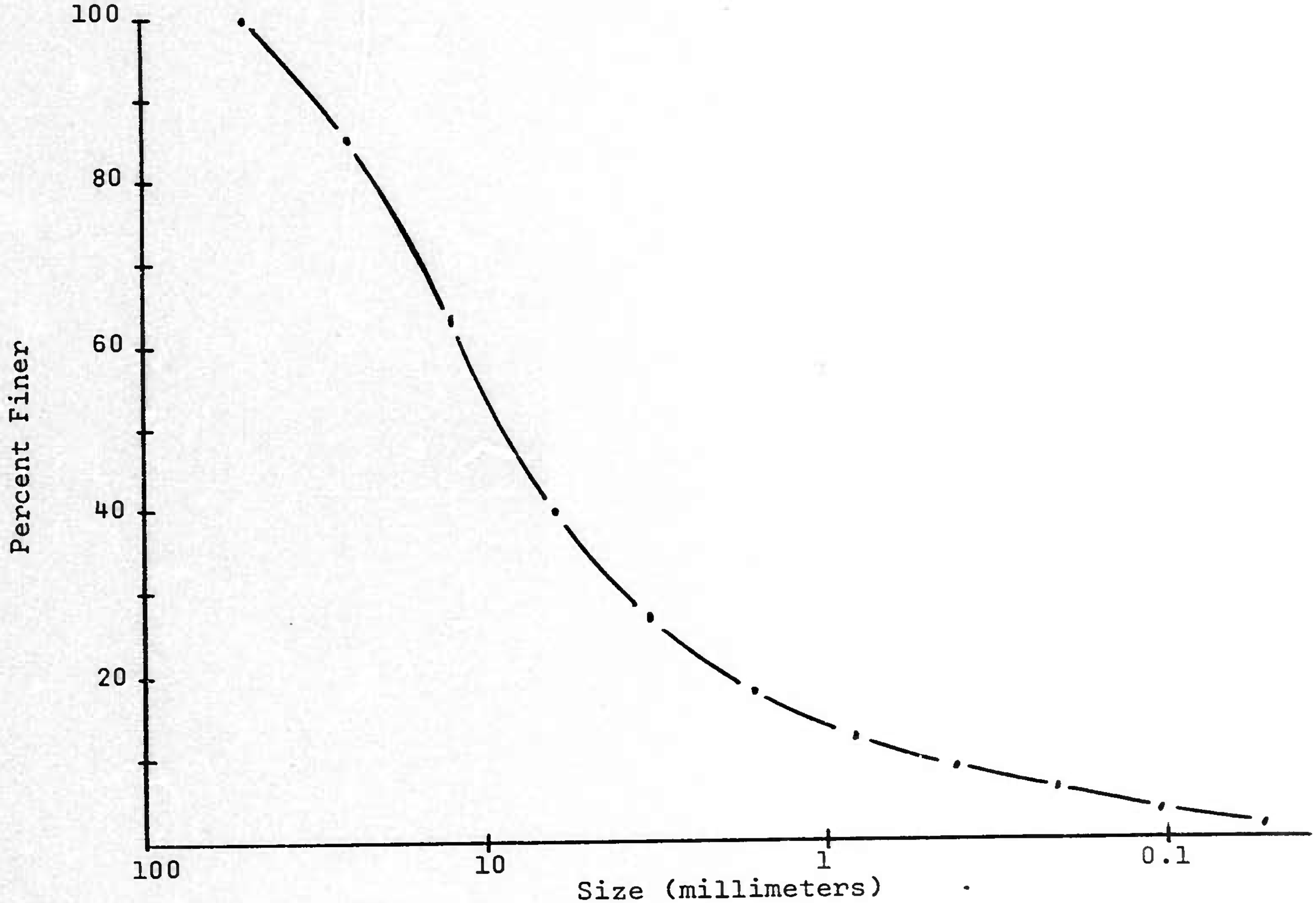

Figure 19. White Pine (1972) Tunnel

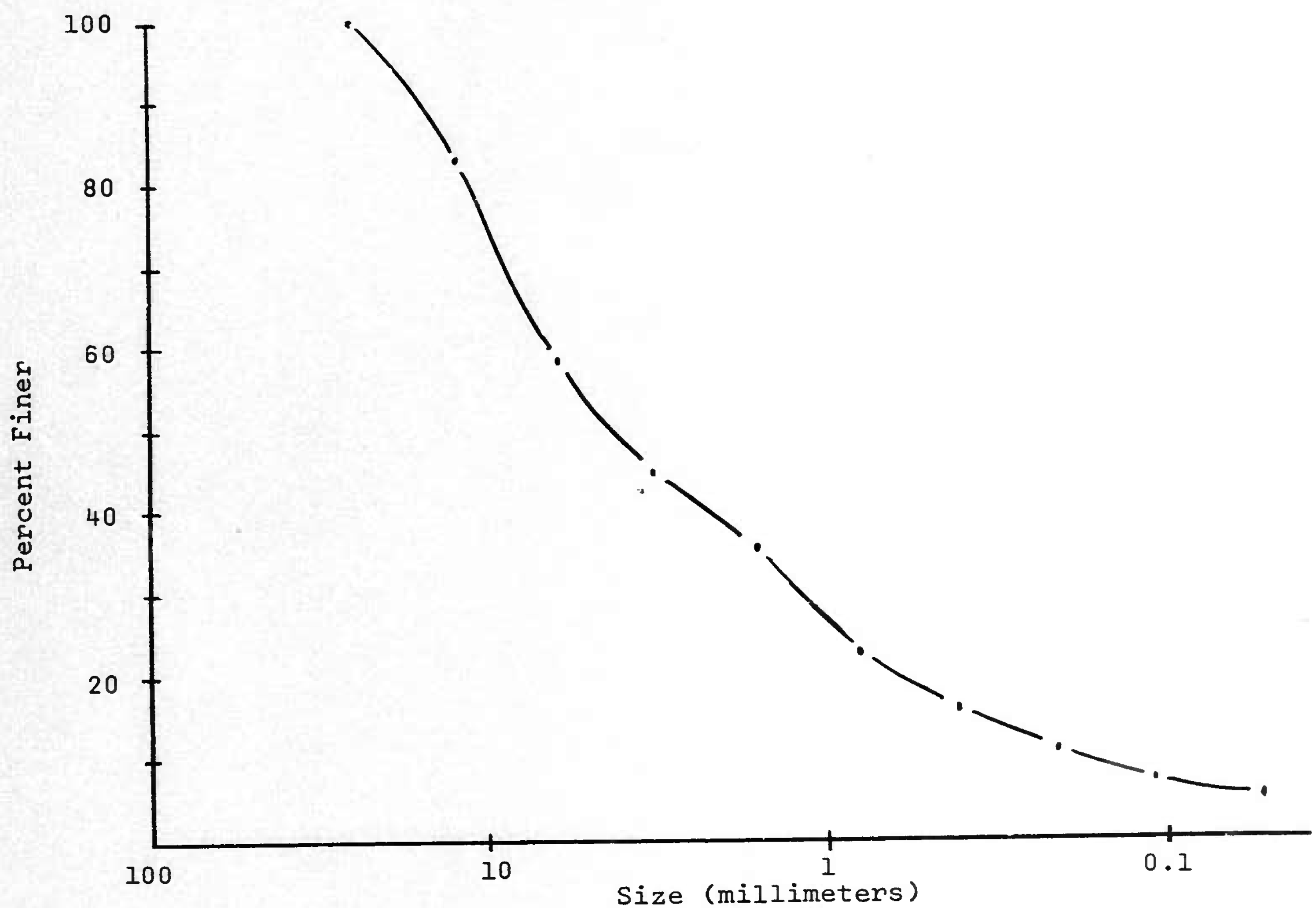

Figure 20. Cleveland Tunnel

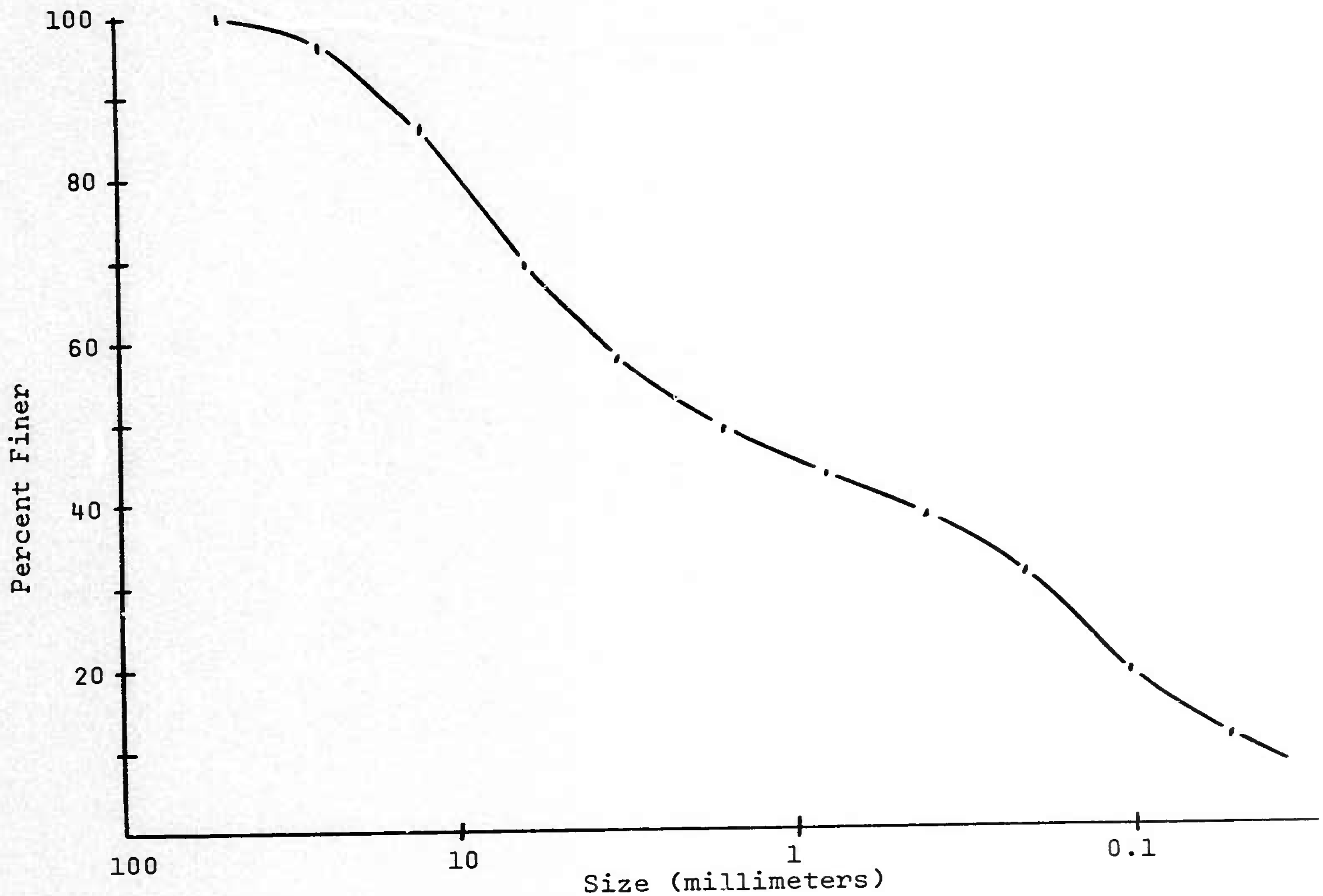

Figure 21. New York Tunnel

APPENDIX IV

MOHR'S ENVELOPE FOR EACH SAMPLE

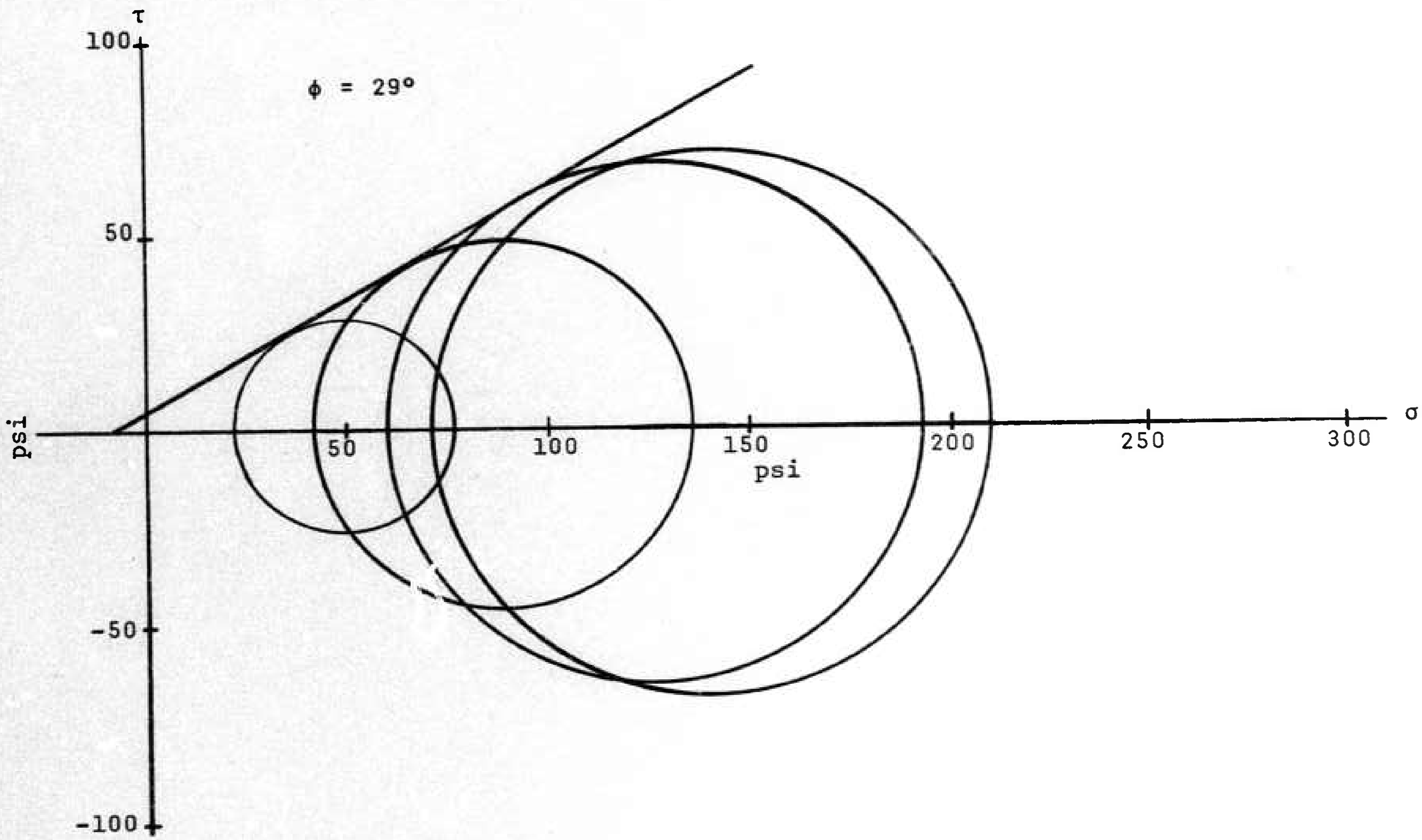

Figure 22. Combined Philadelphia #1

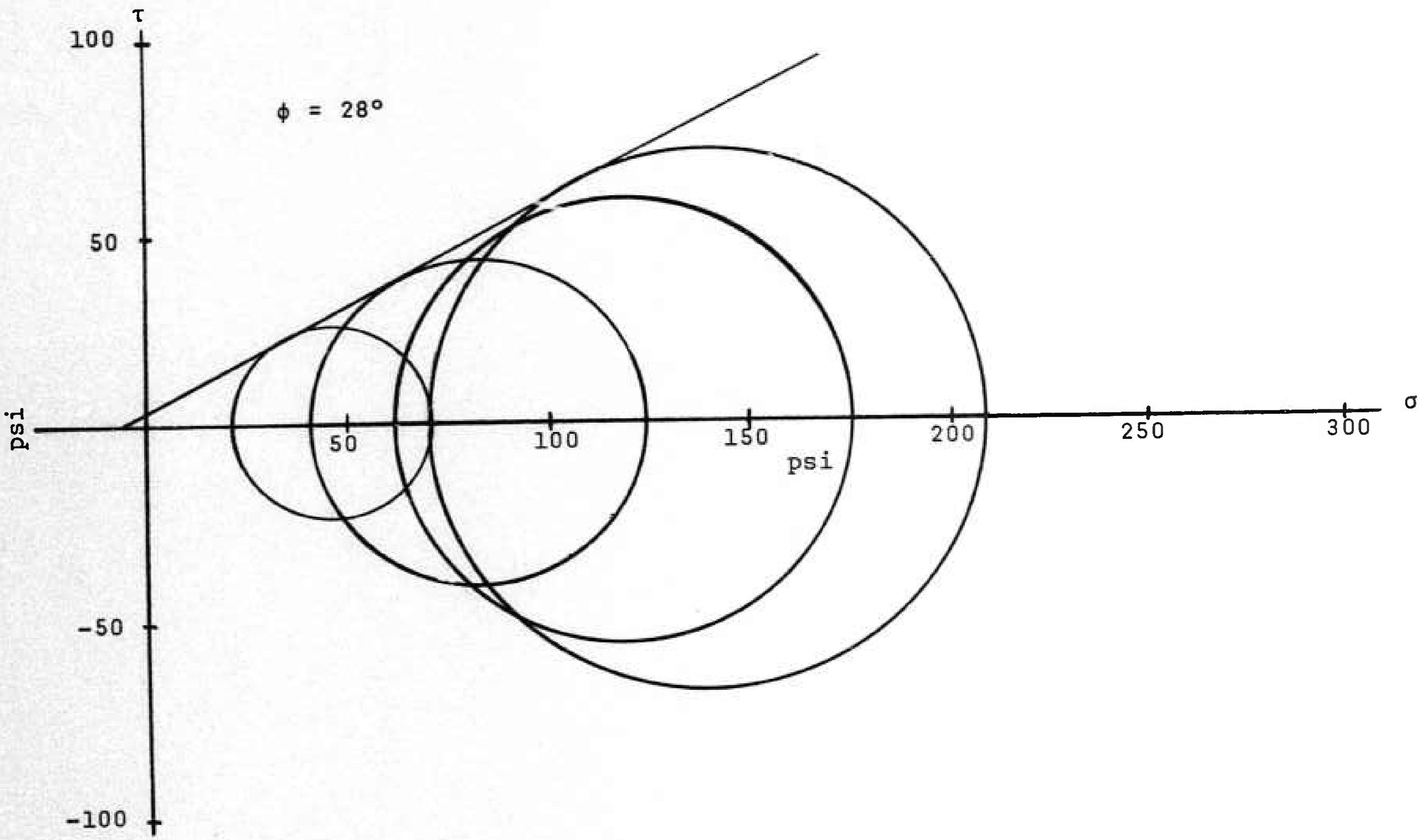

Figure 23. Combined Philadelphia #2

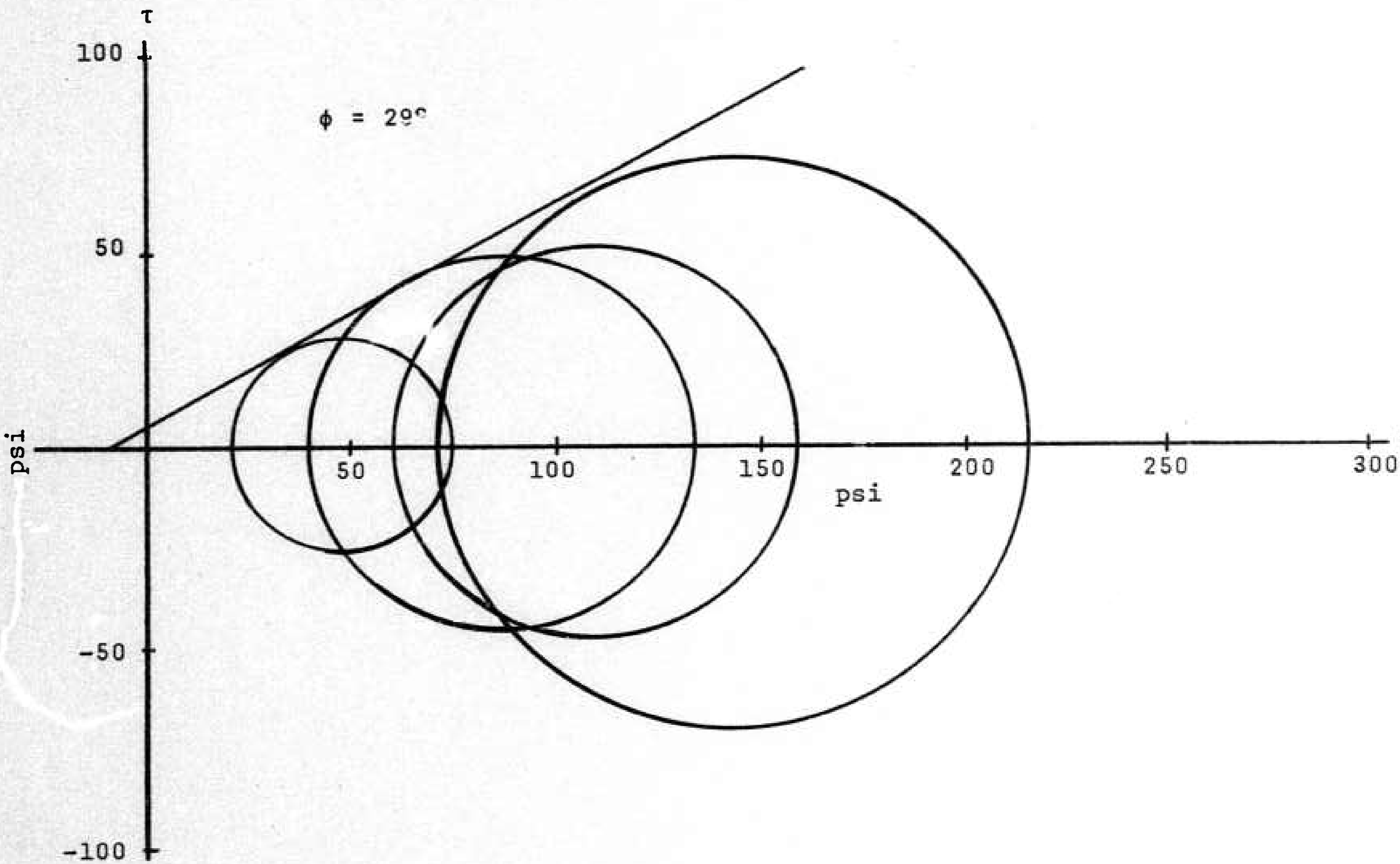

Figure 24. #6 Mesh Philadelphia

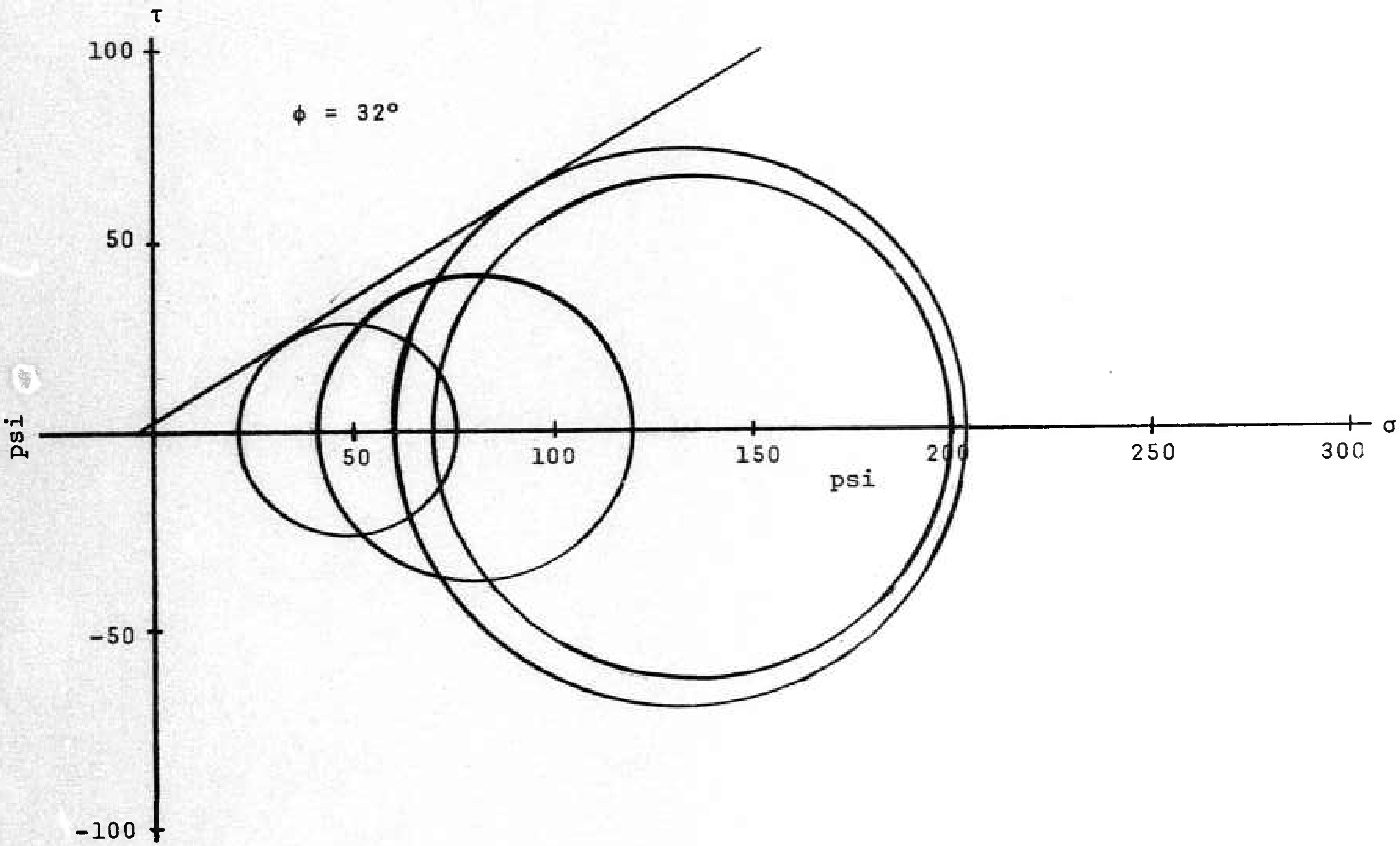

Figure 25. #40 Mesh Philadelphia #1

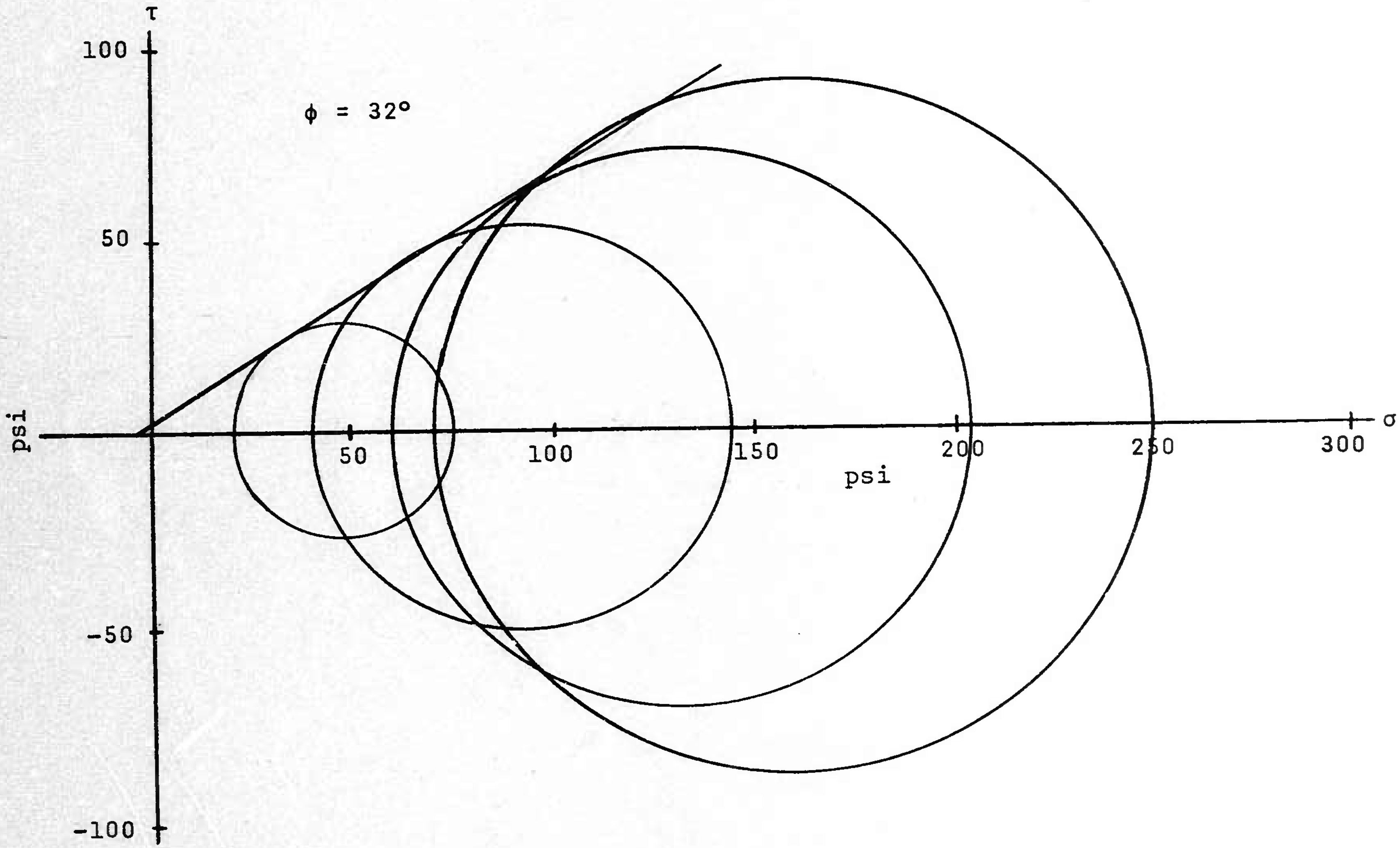

Figure 26. #40 Mesh Philadelphia #2

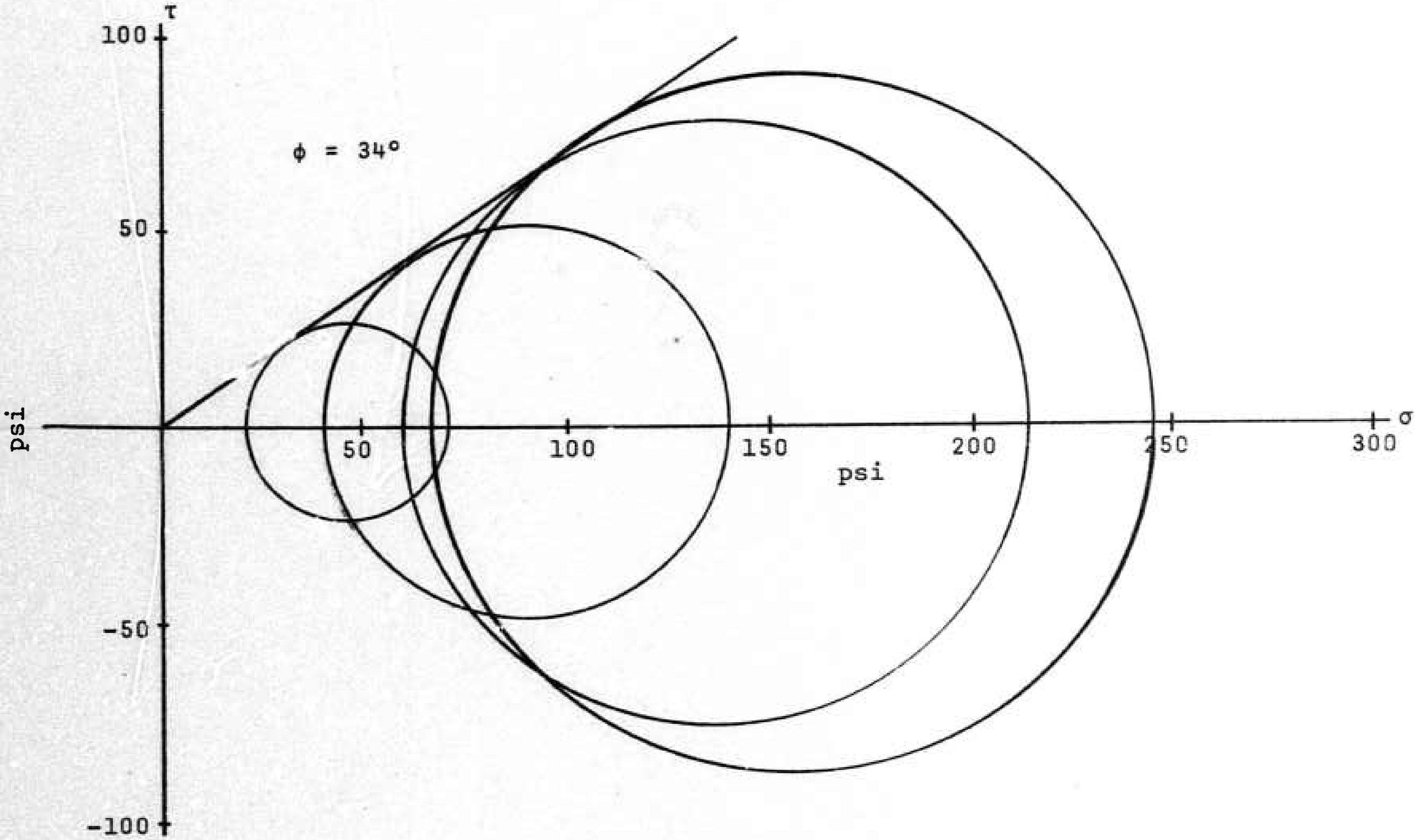

Figure 27. #140 Mesh Philadelphia

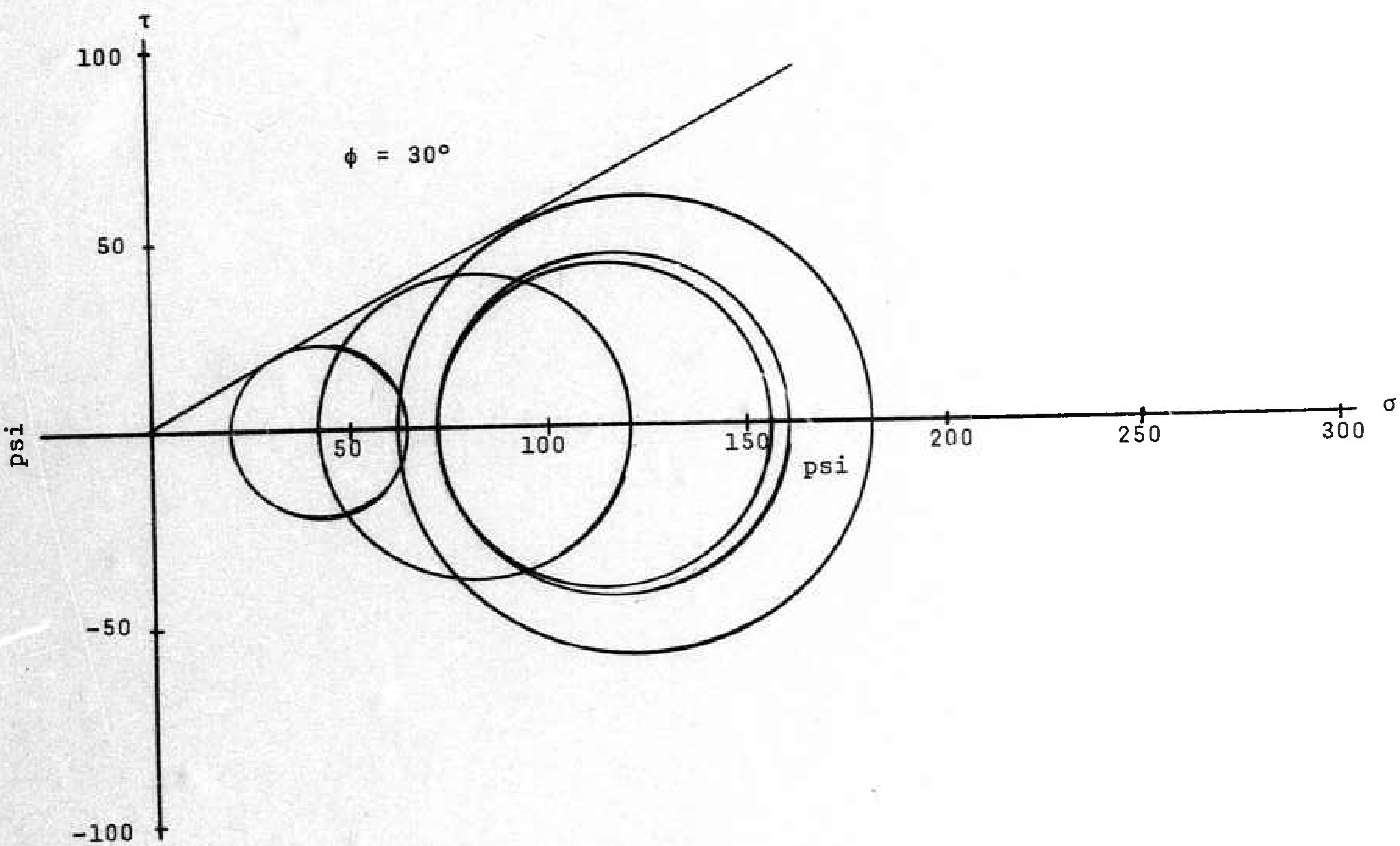

Figure 28. Combined Farmington Year I

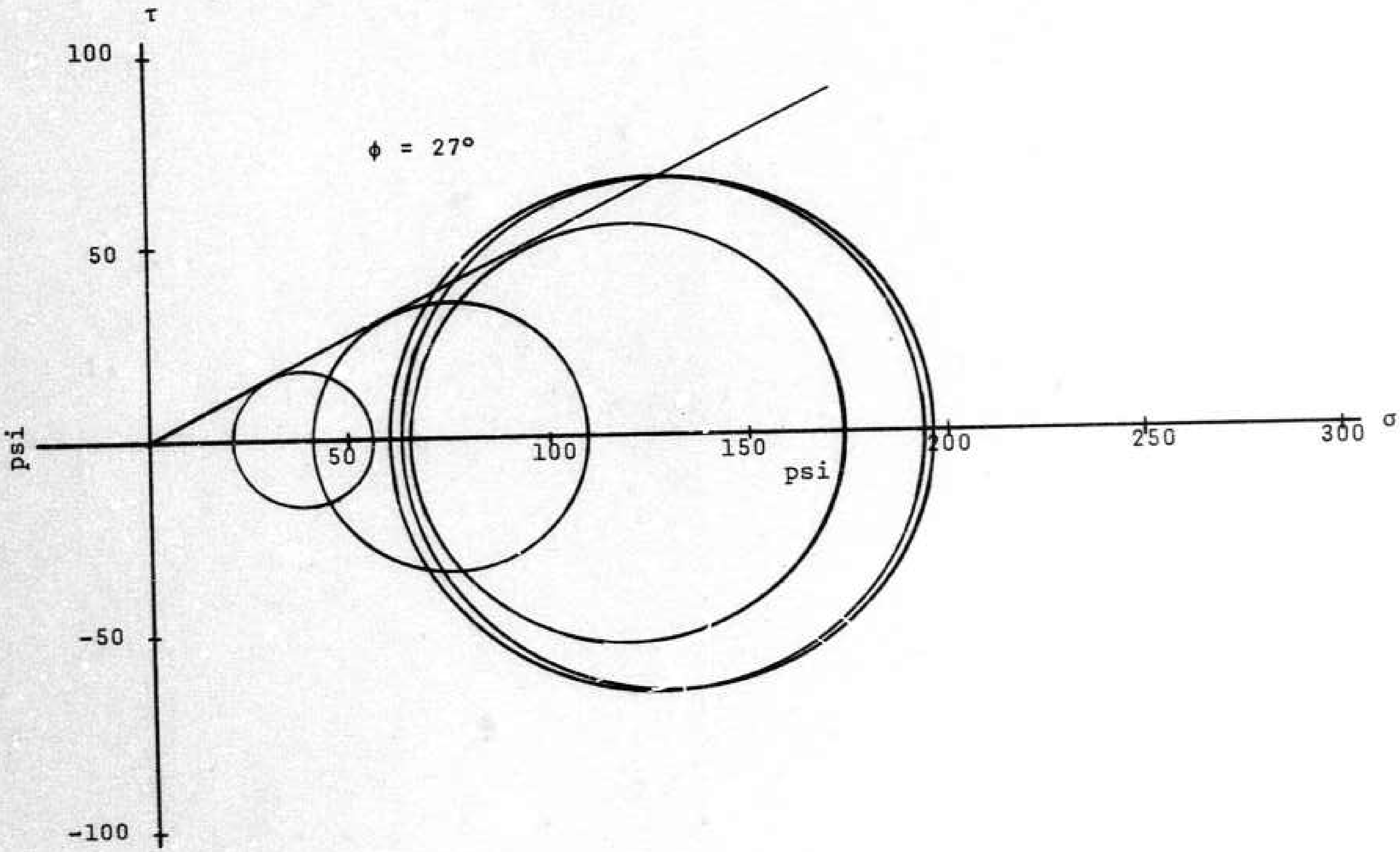

Figure 29.   #20 Mesh Farmington

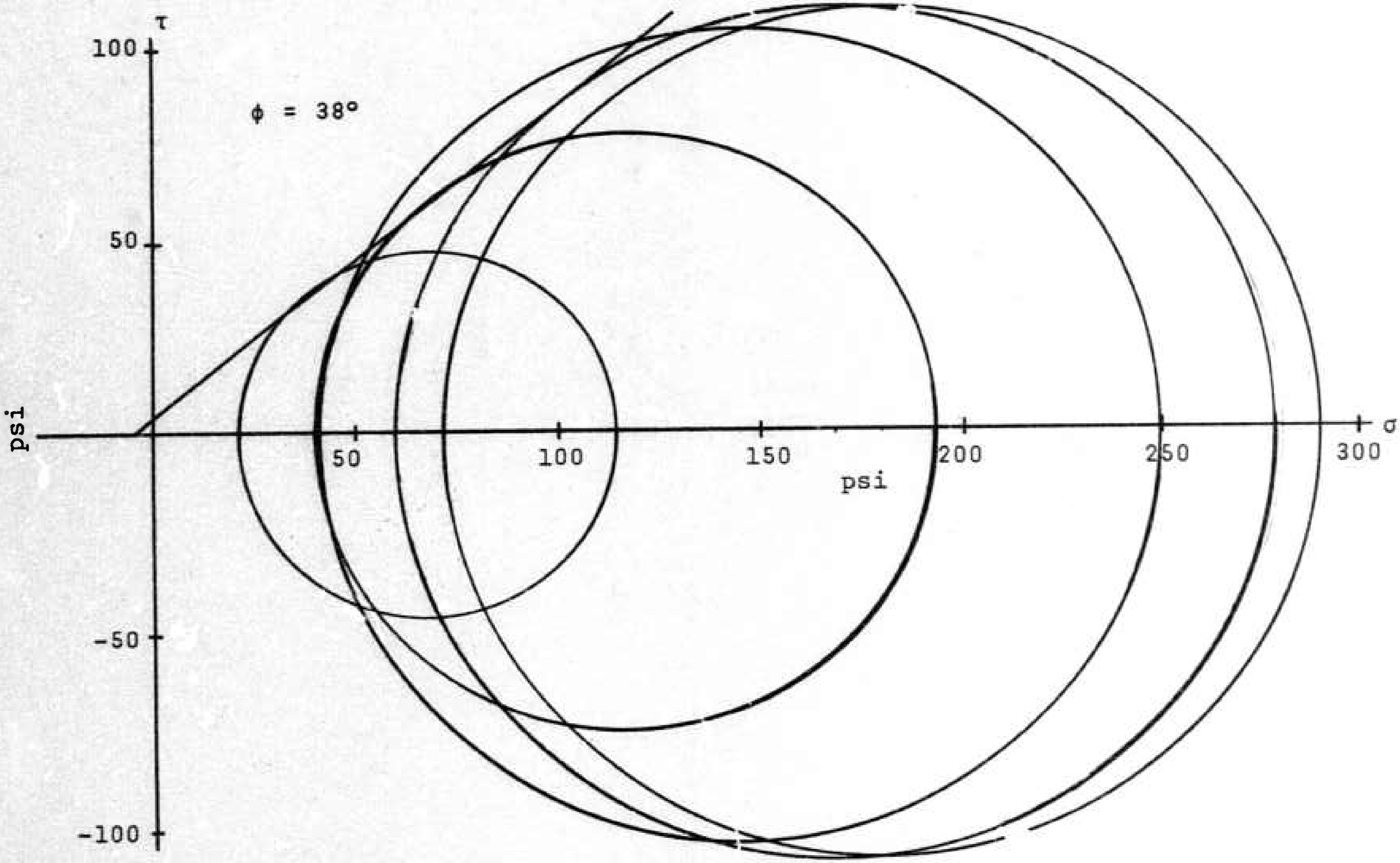

Figure 30. #40 Mesh Farmington Test #1

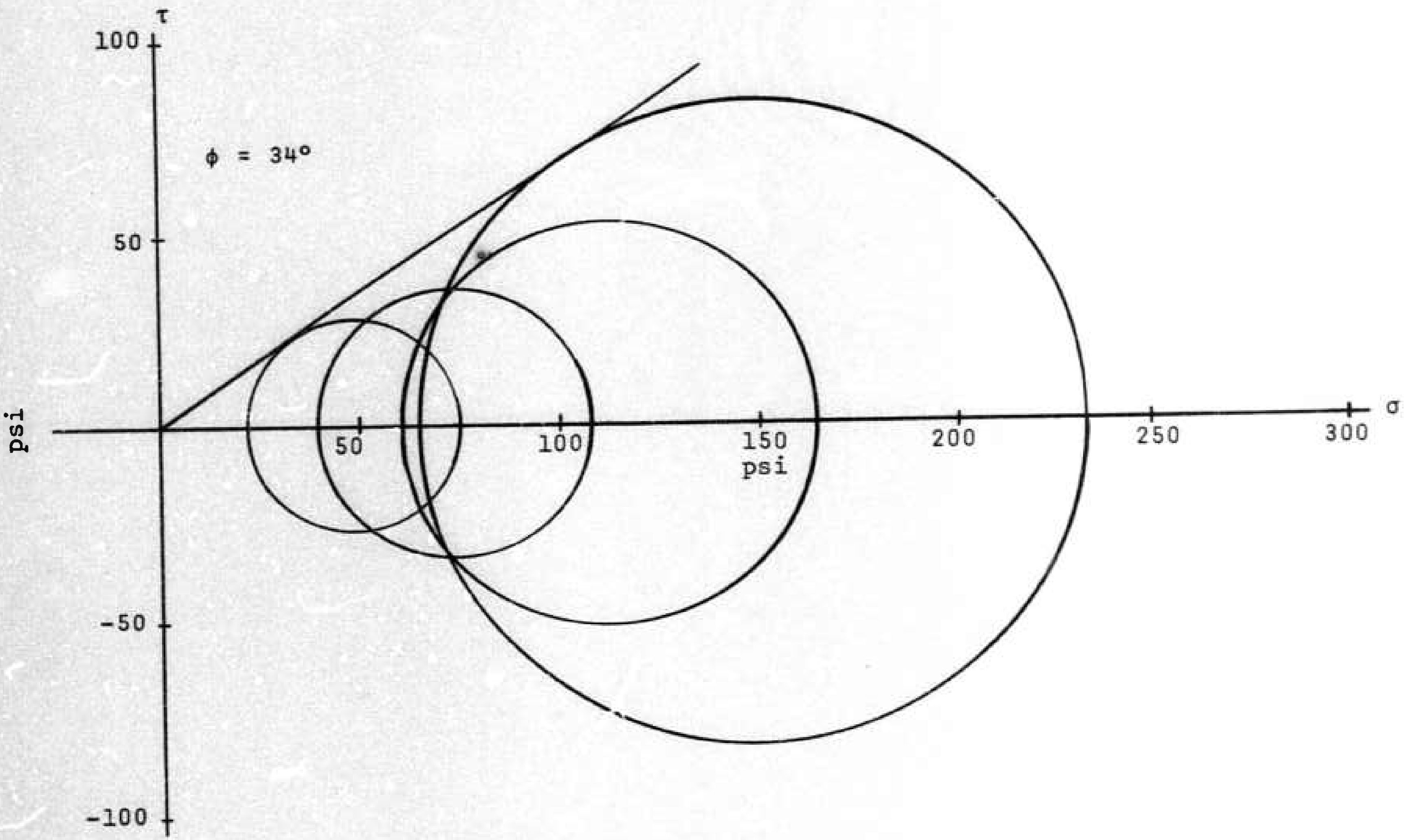

Figure 31. #40 Mesh Farmington Test #2

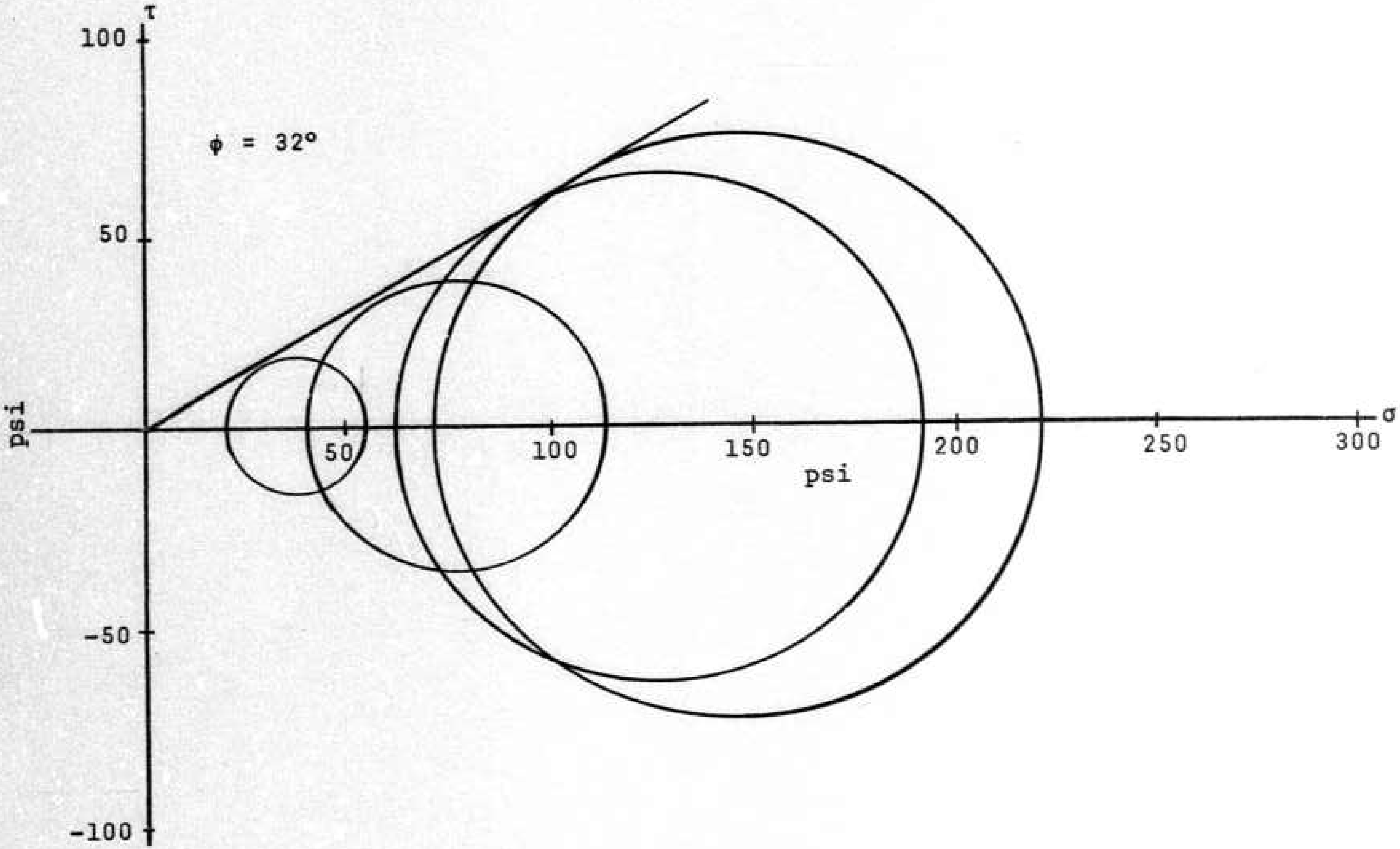

Figure 32. #140 Mesh Farmington Test #1

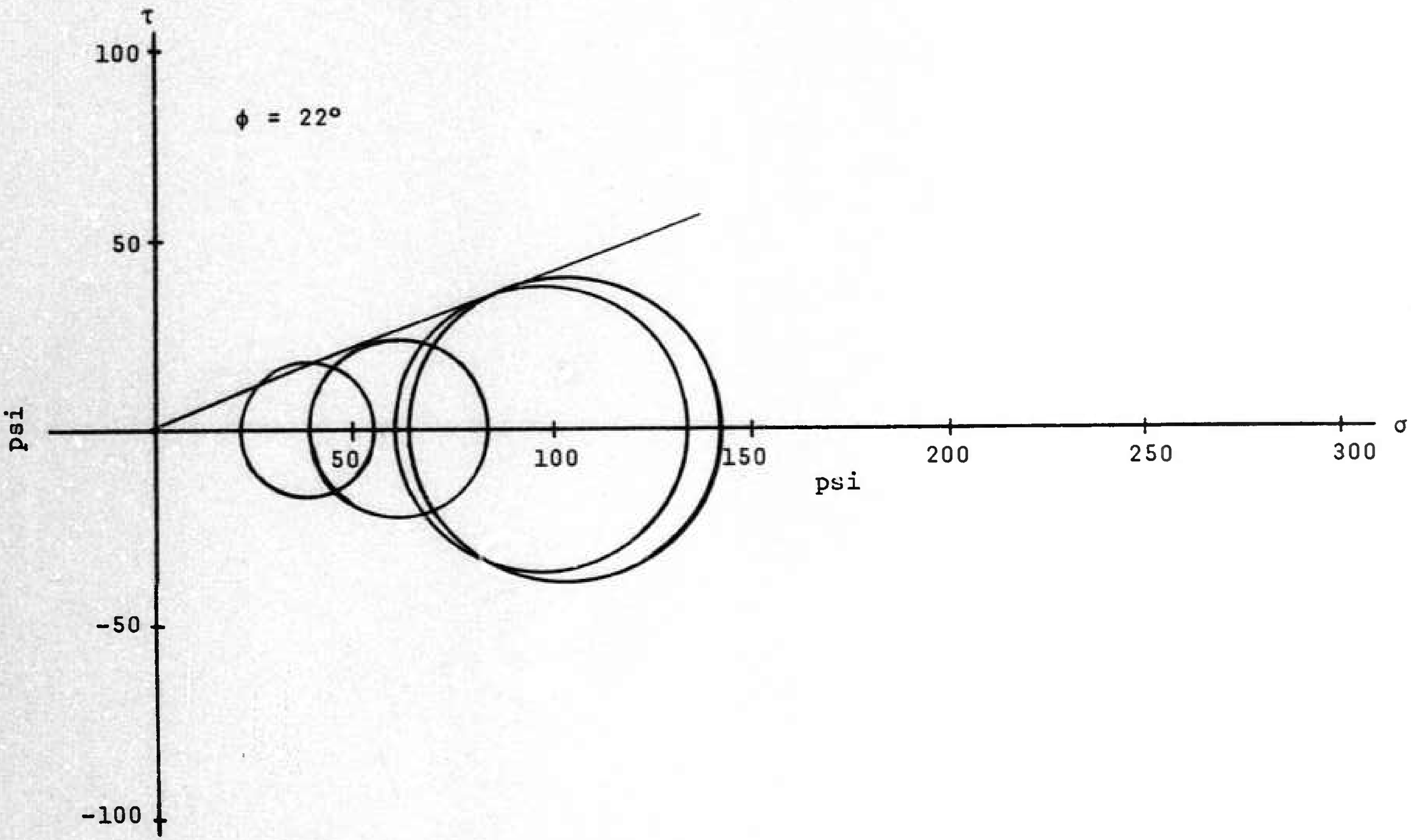

Figure 33. #140 Mesh Farmington Test #2

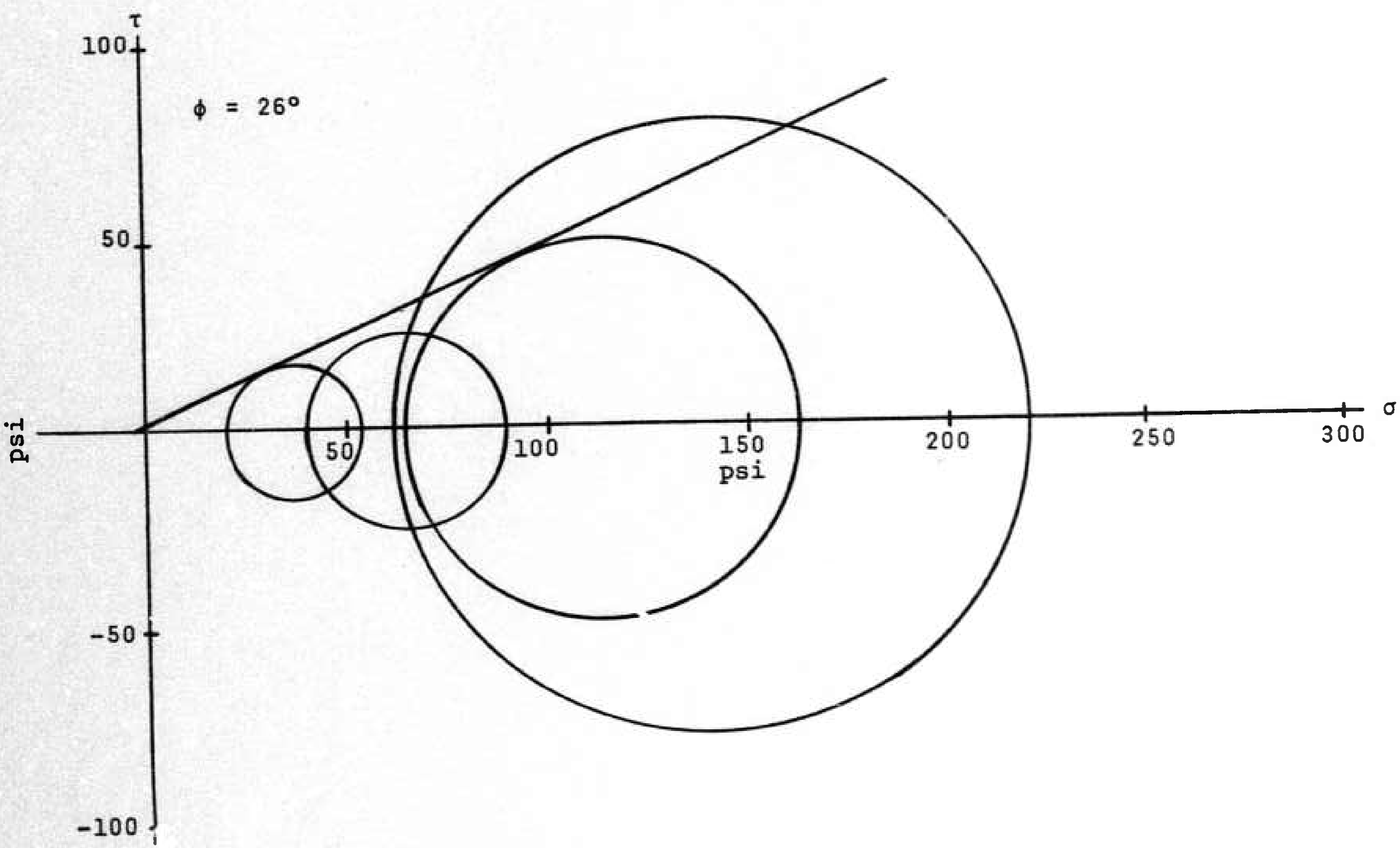

Figure 34. #140 Mesh Farmington Test #3

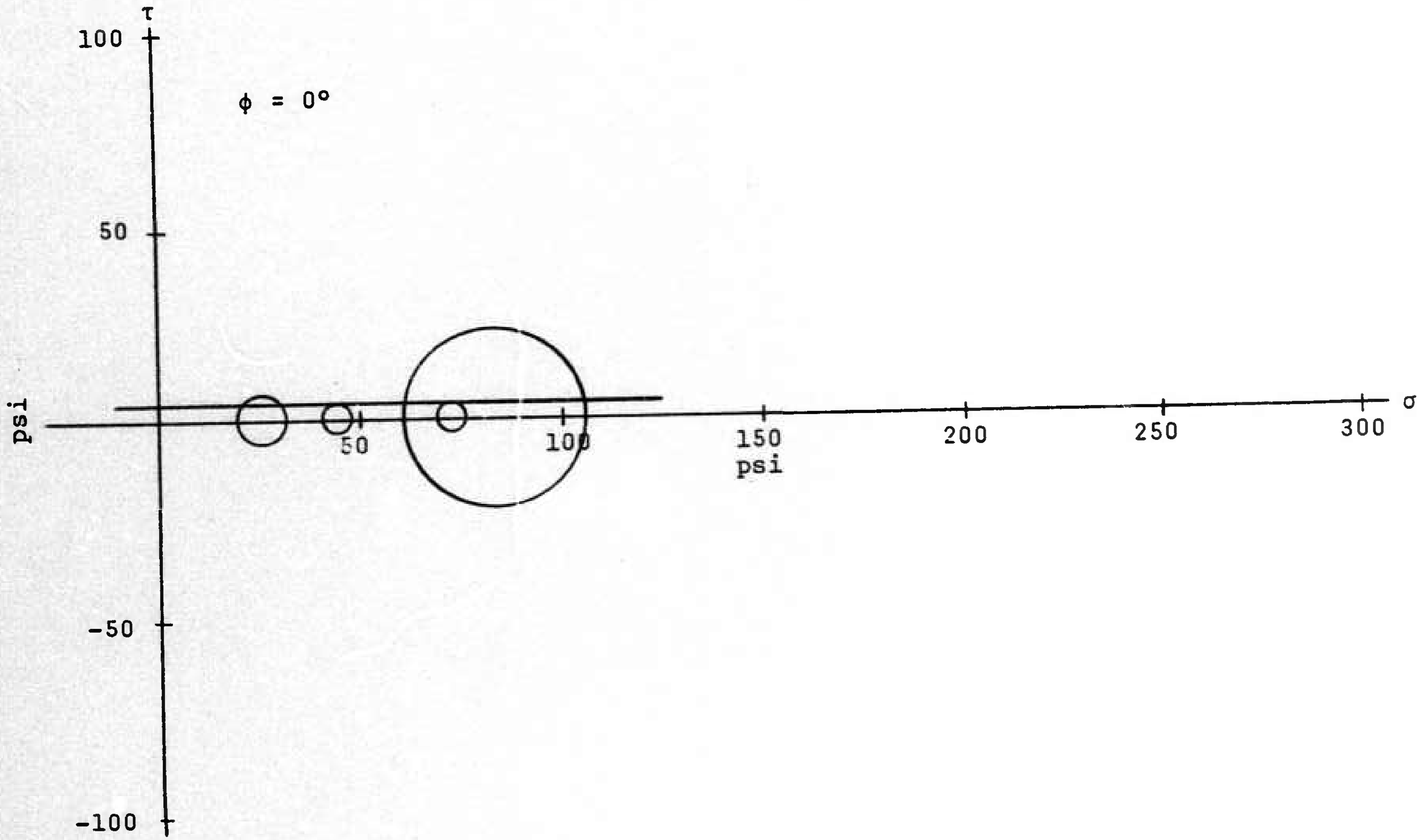

Figure 35. Combined Heber City

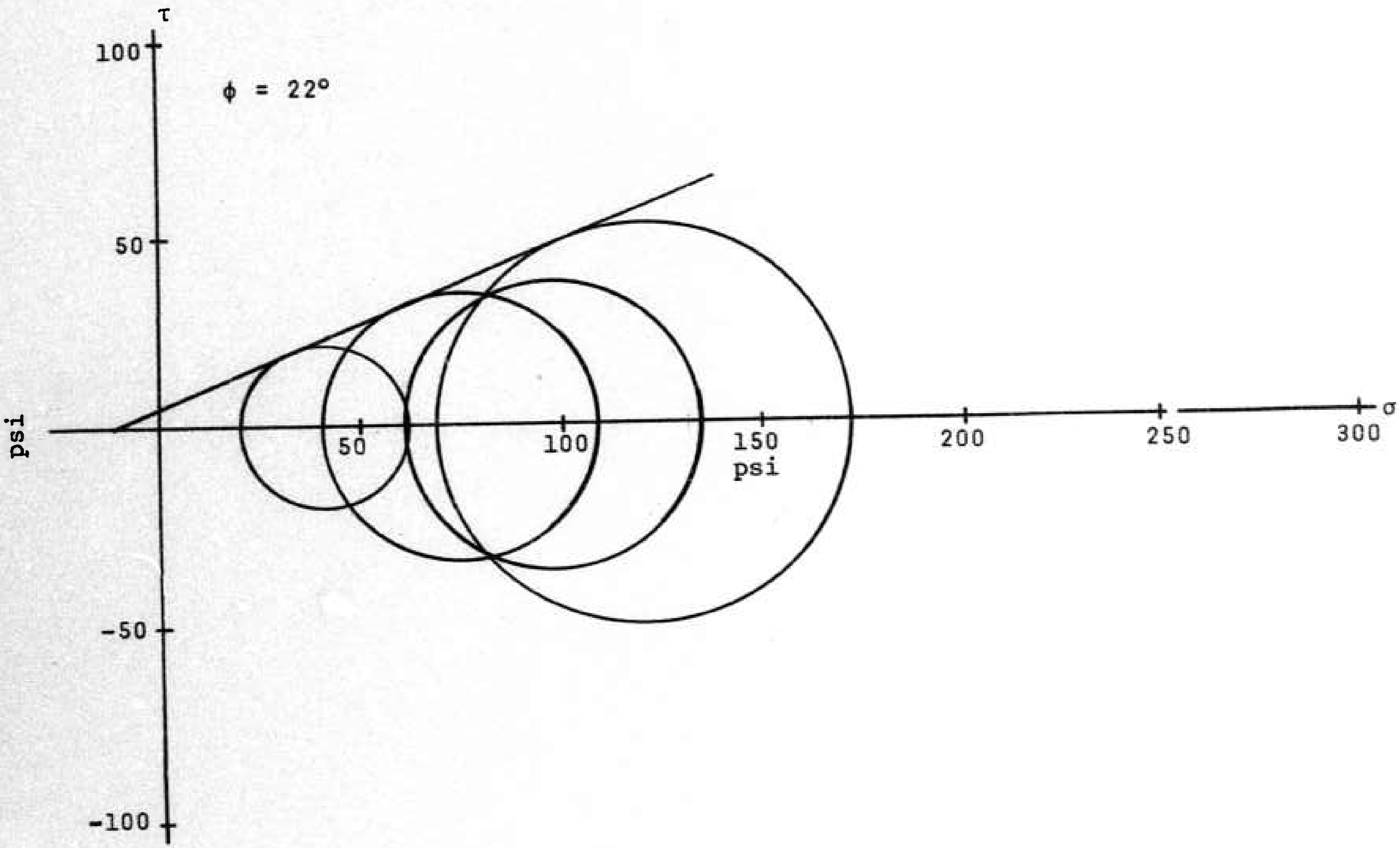

Figure 36. #12 Mesh Heber City

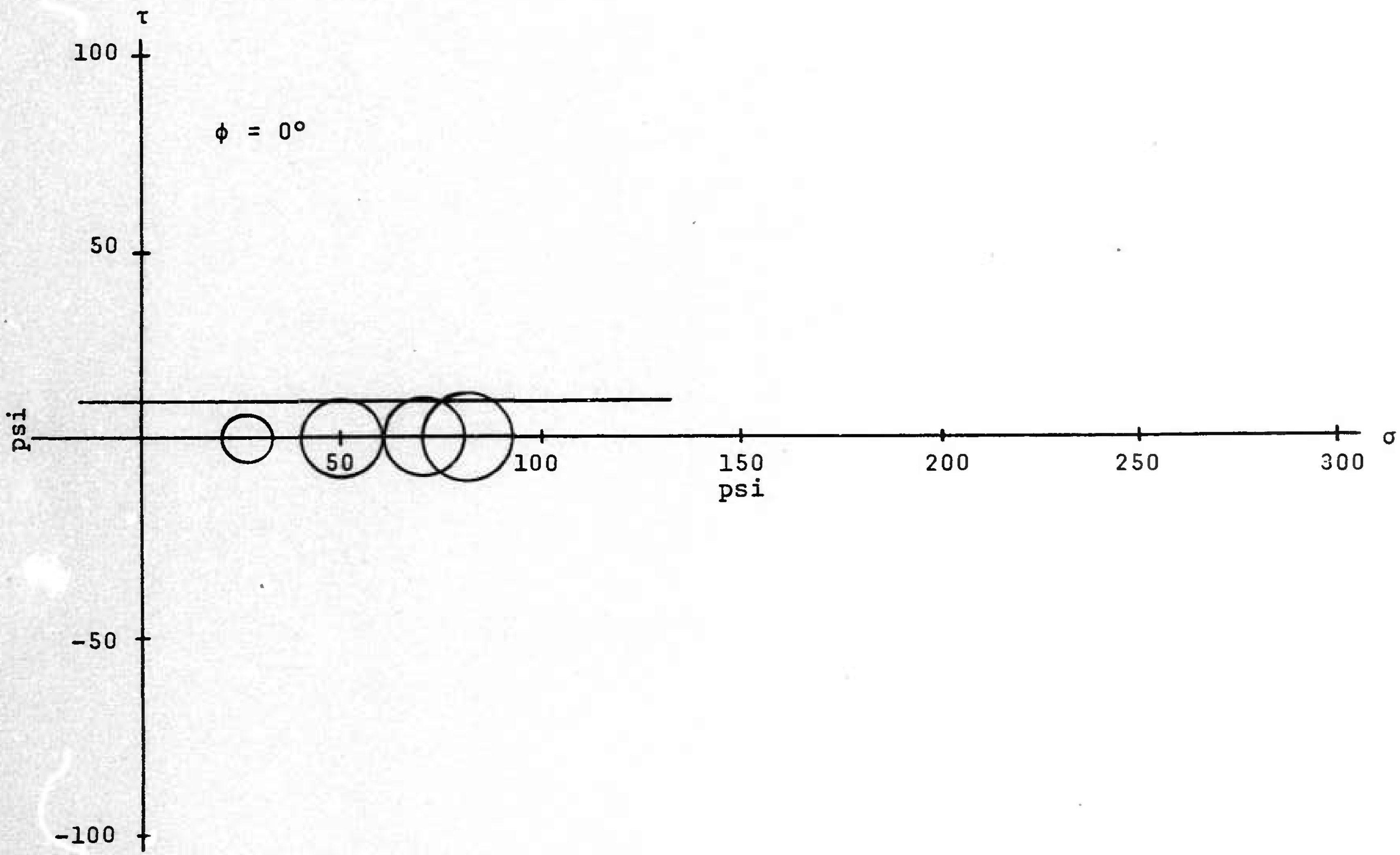

Figure 37. #40 Mesh Heber City

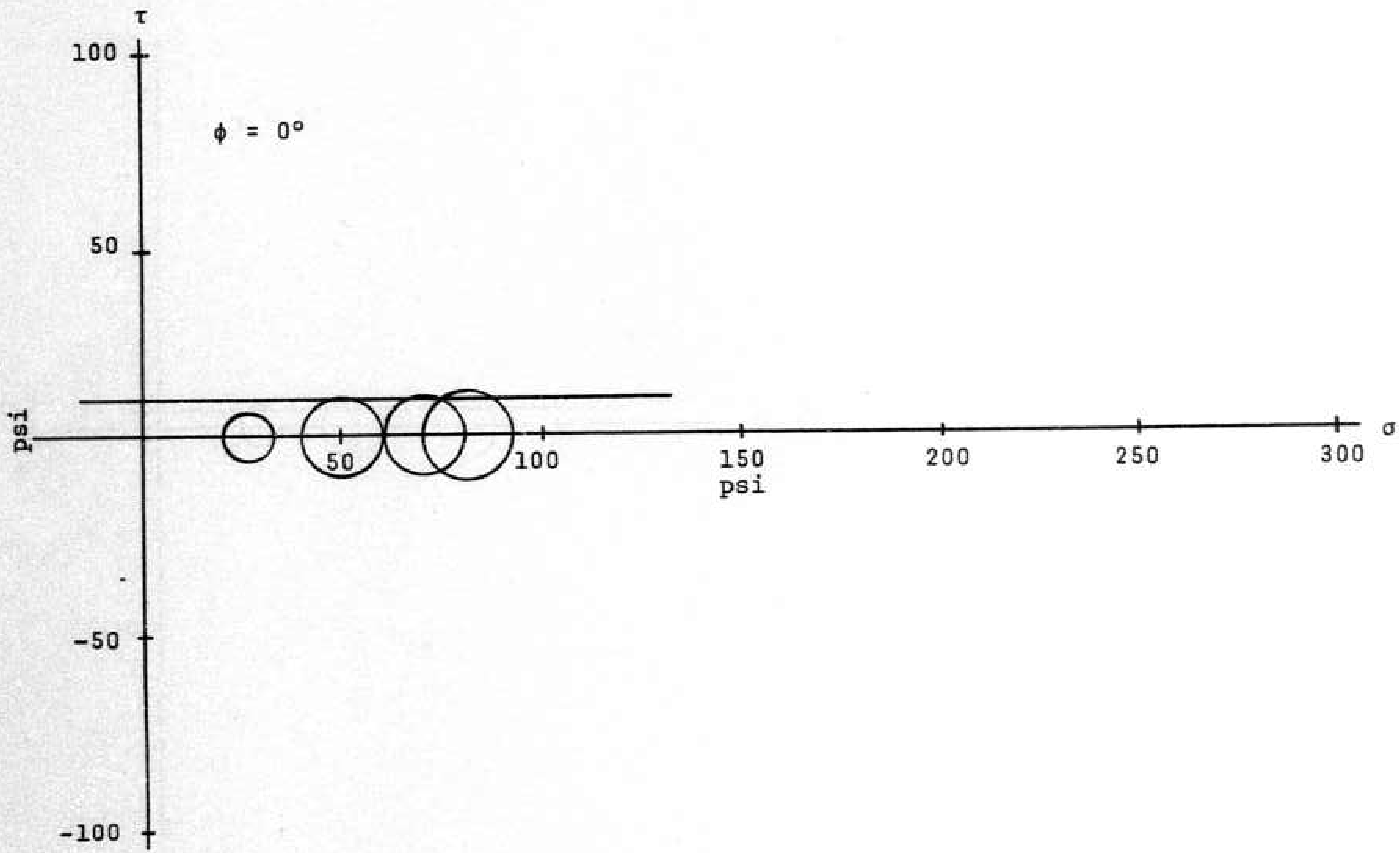

Figure 37. #40 Mesh Heber City

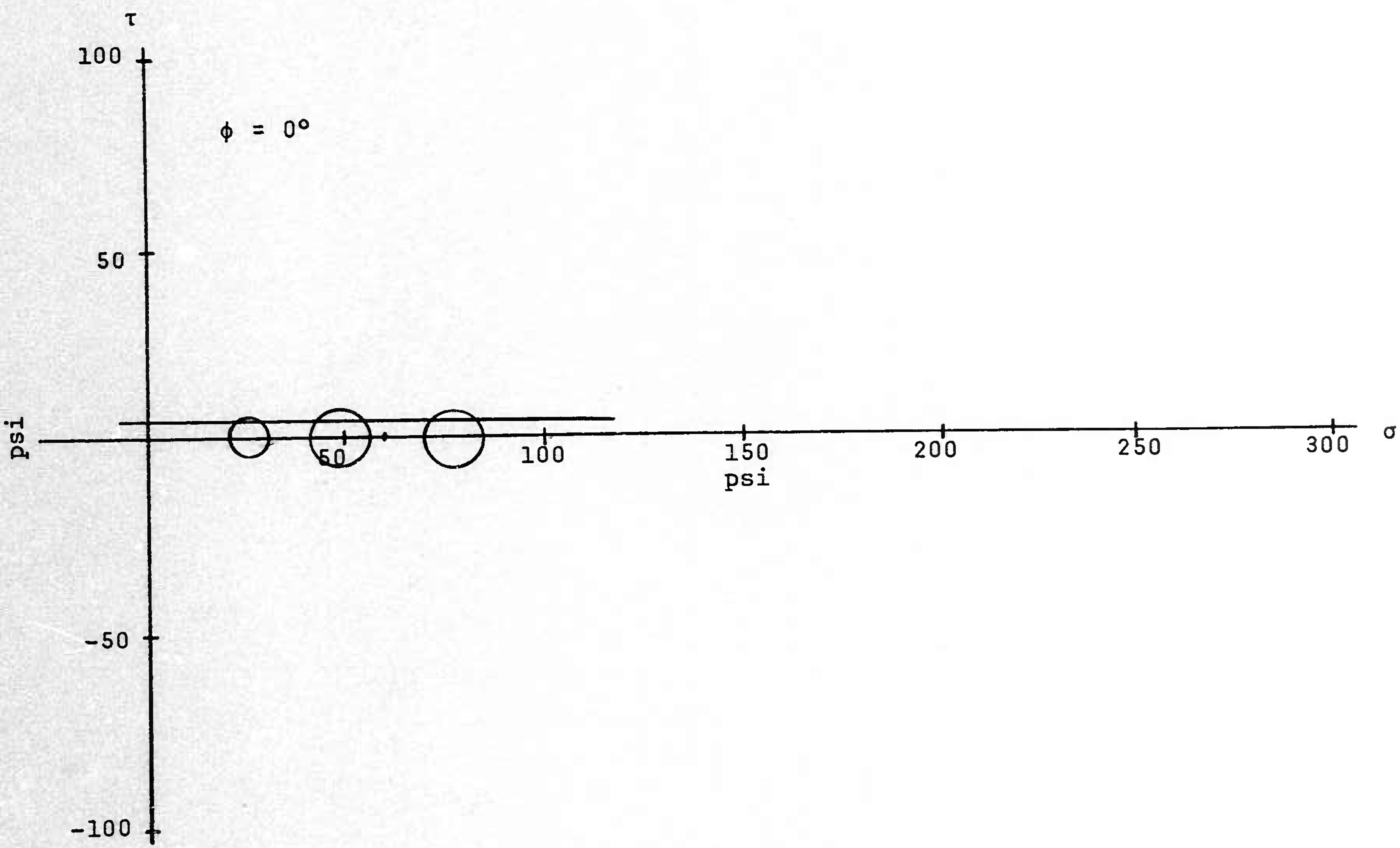

Figure 38. #140 Mesh Heber City

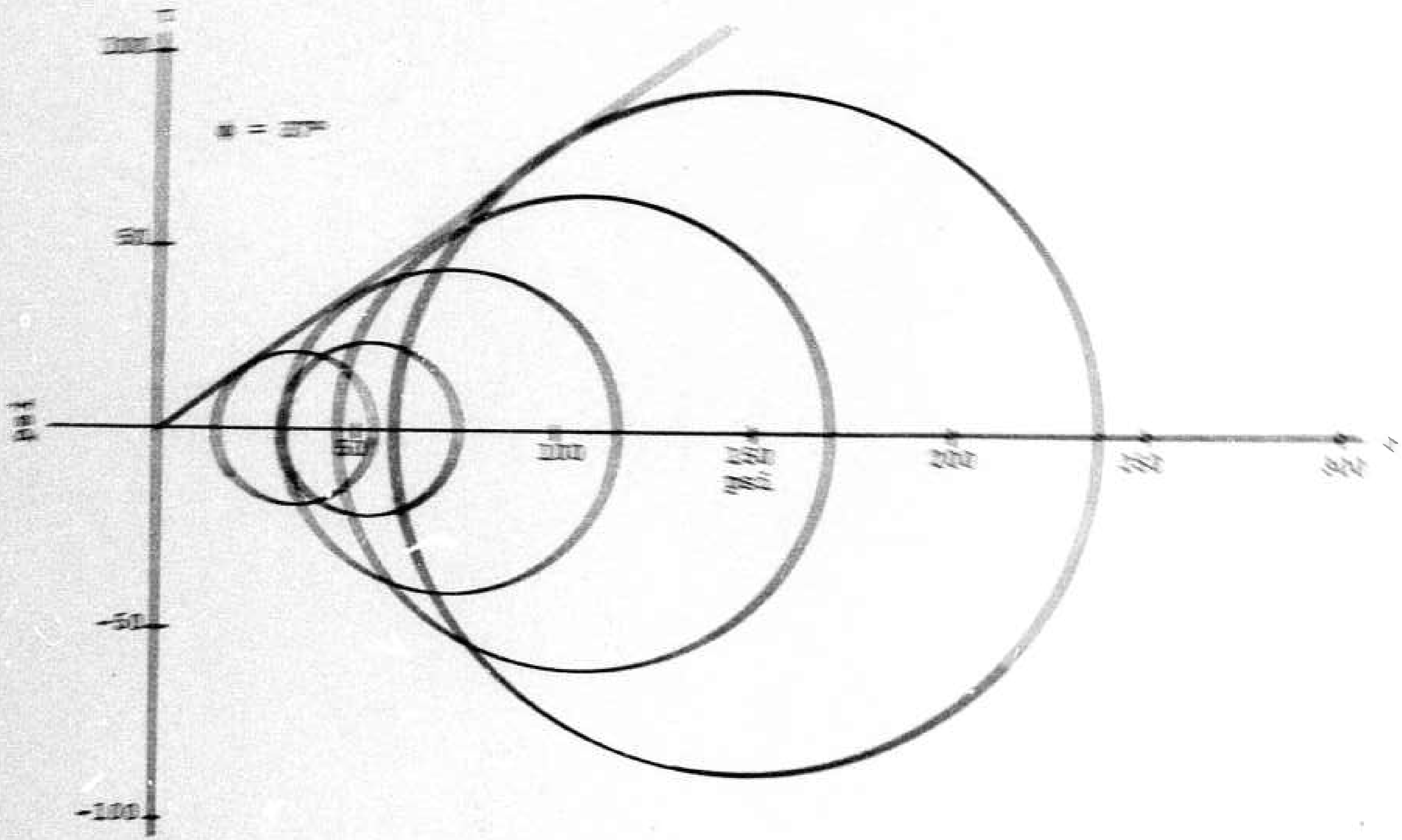

Figure 39. Combined Nast

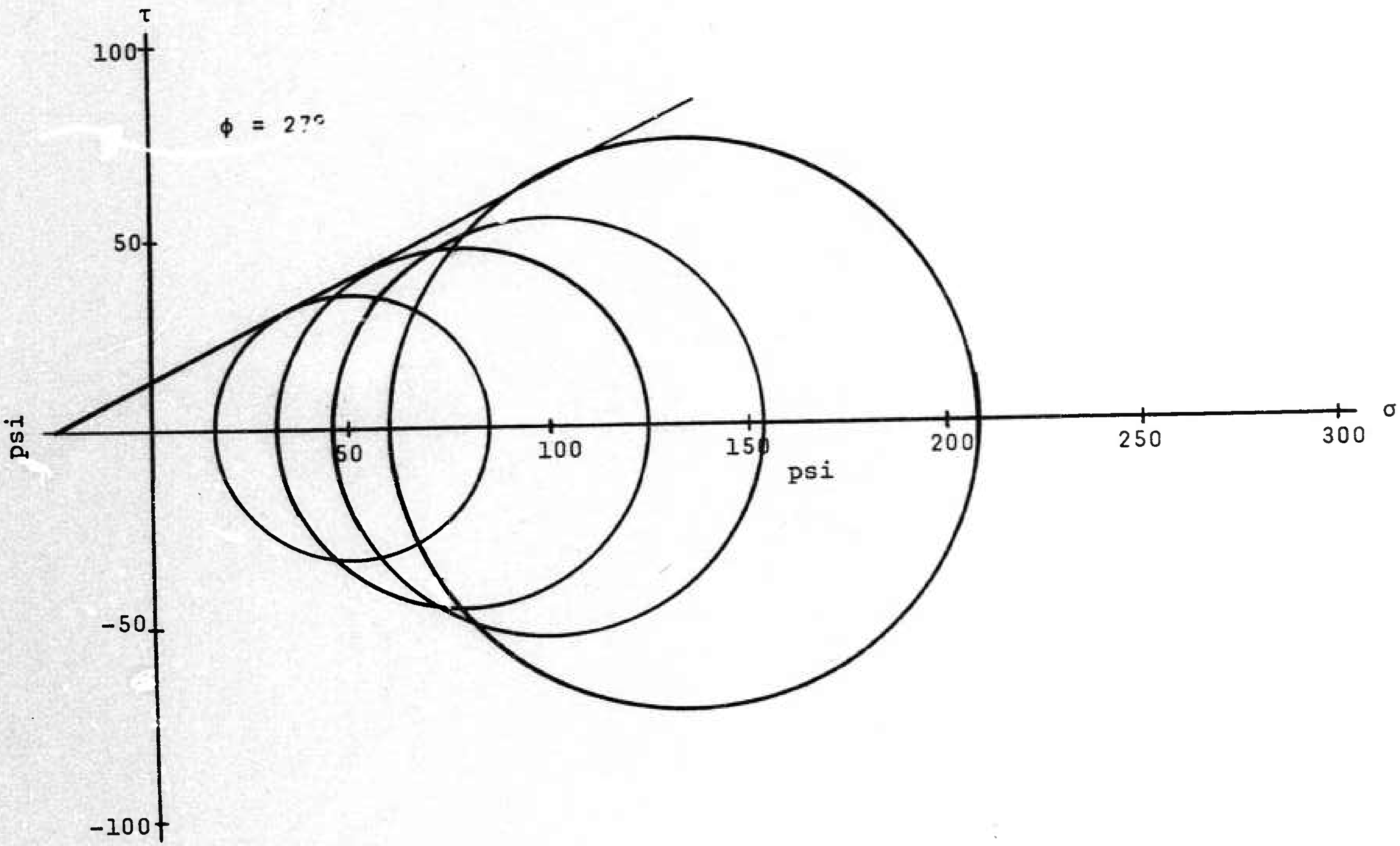

Figure 40. #6 Mesh Nast

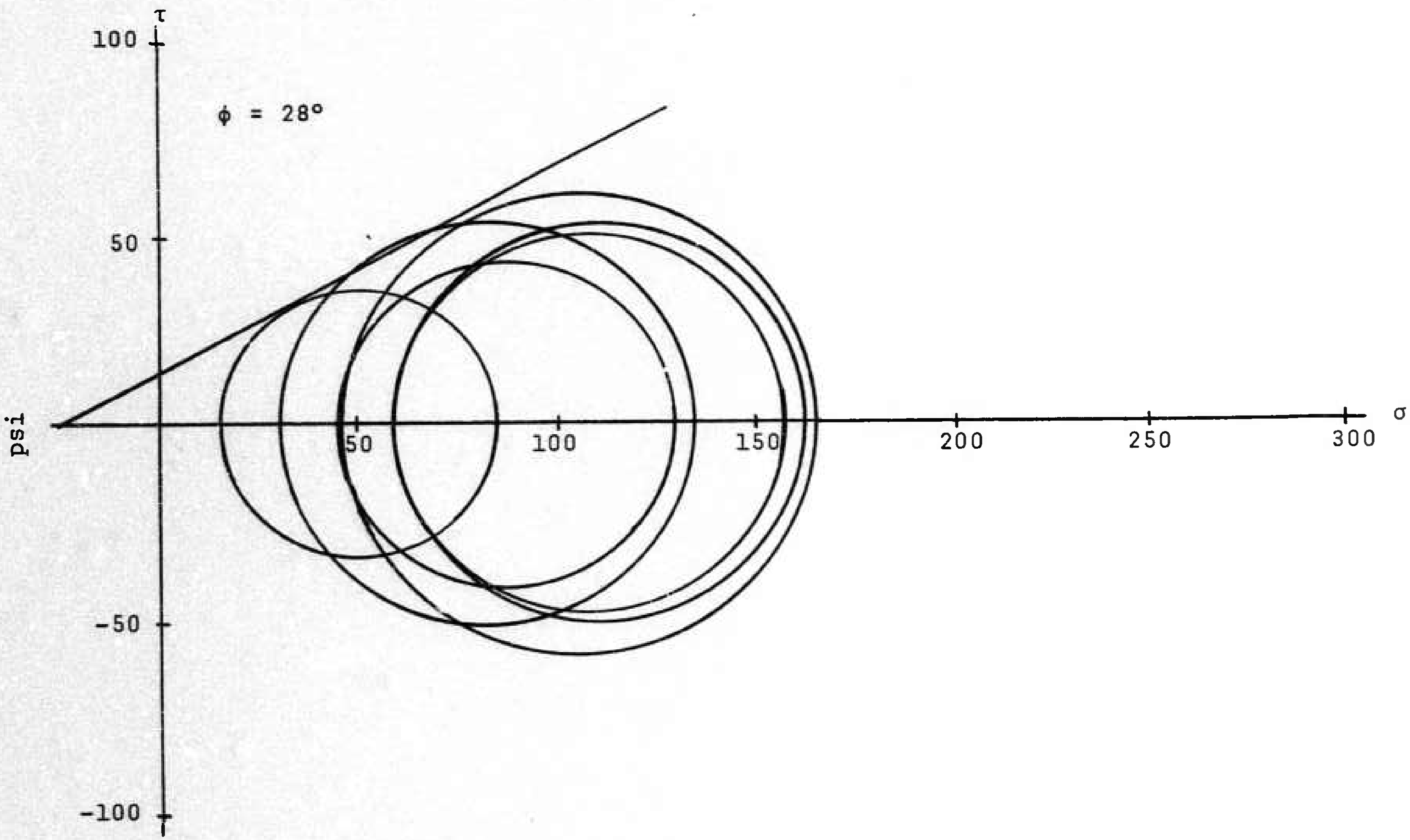

Figure 41. #40 Mesh Nast

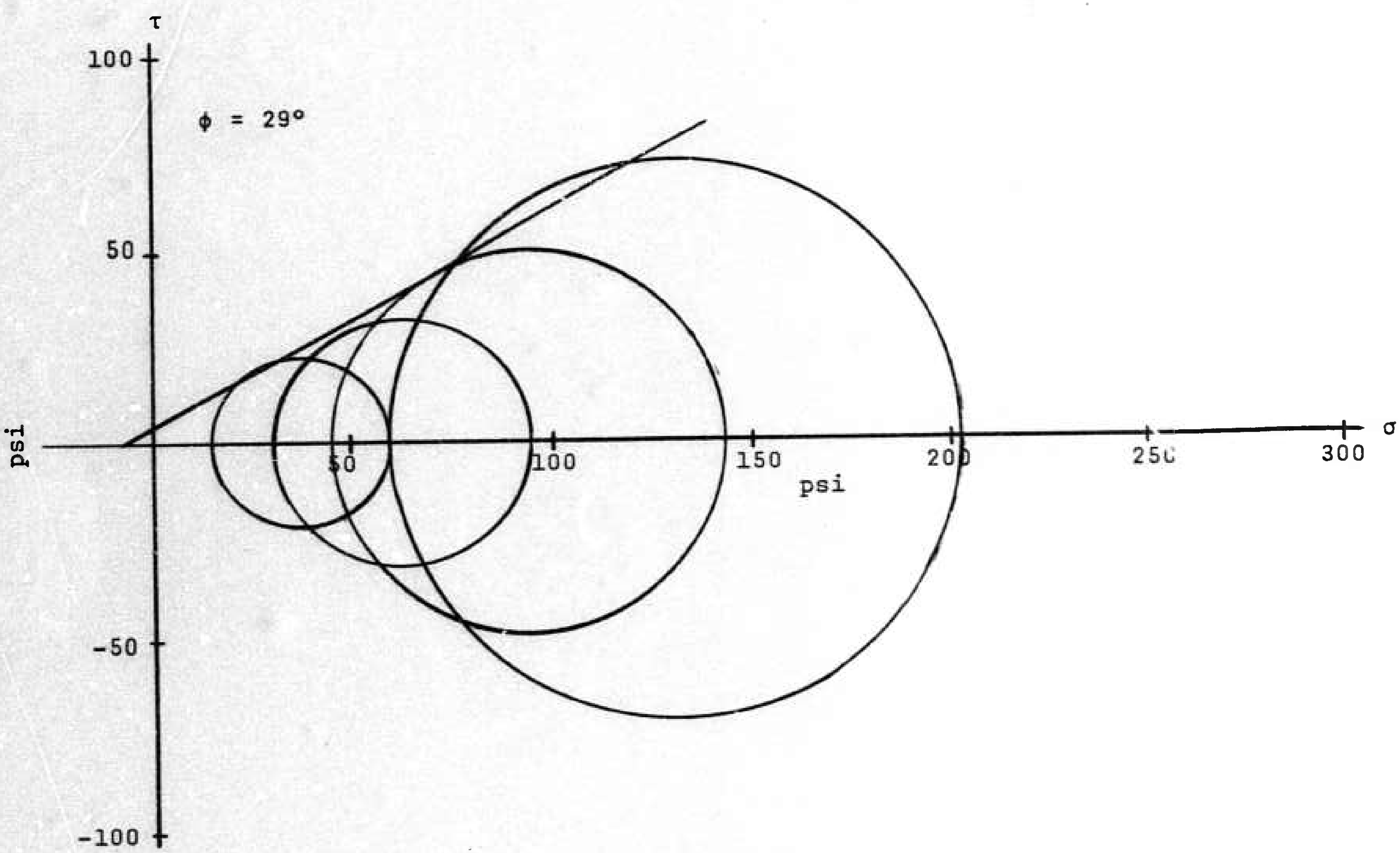

Figure 42. #140 Mesh Nast

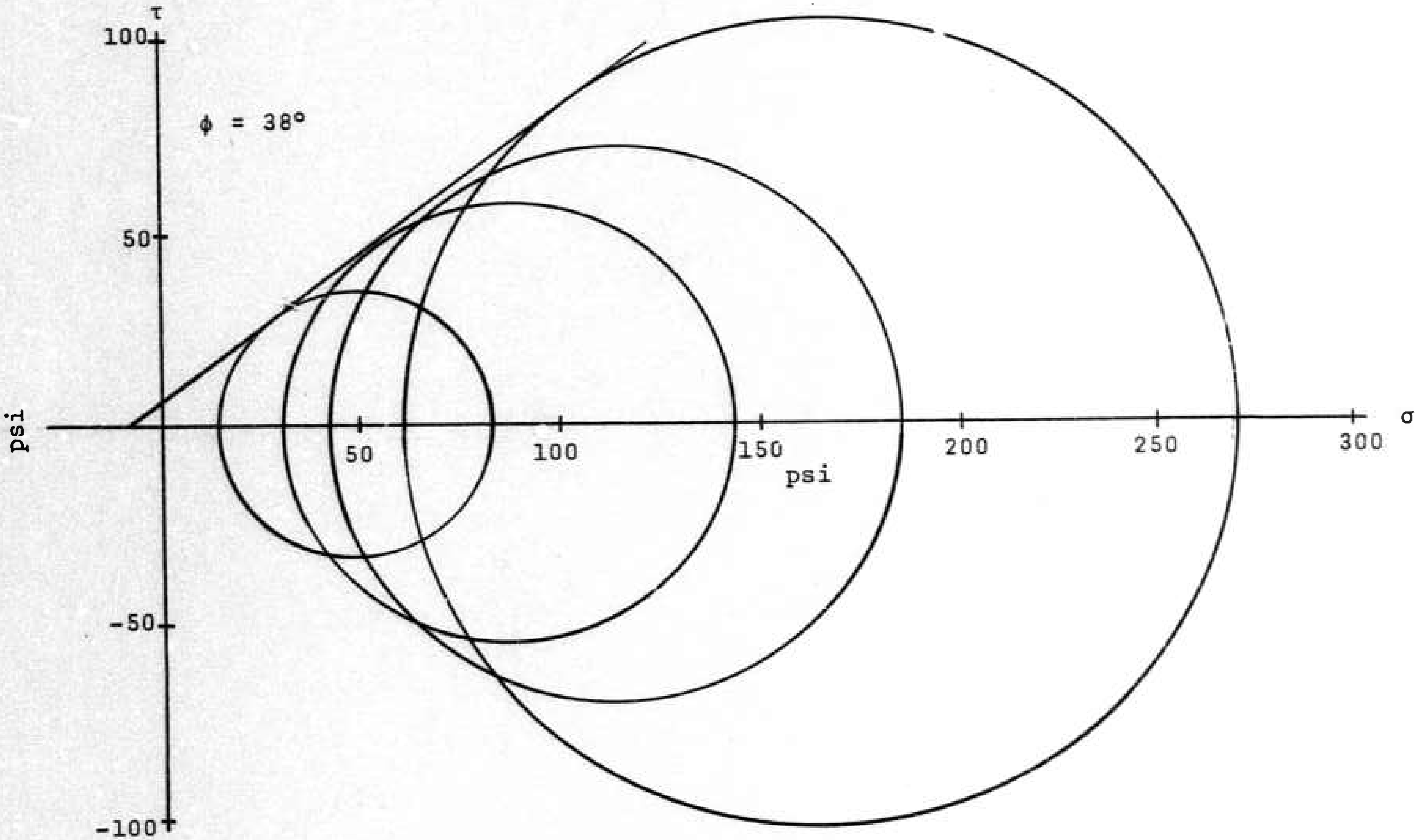

Figure 43. Combined Chicago

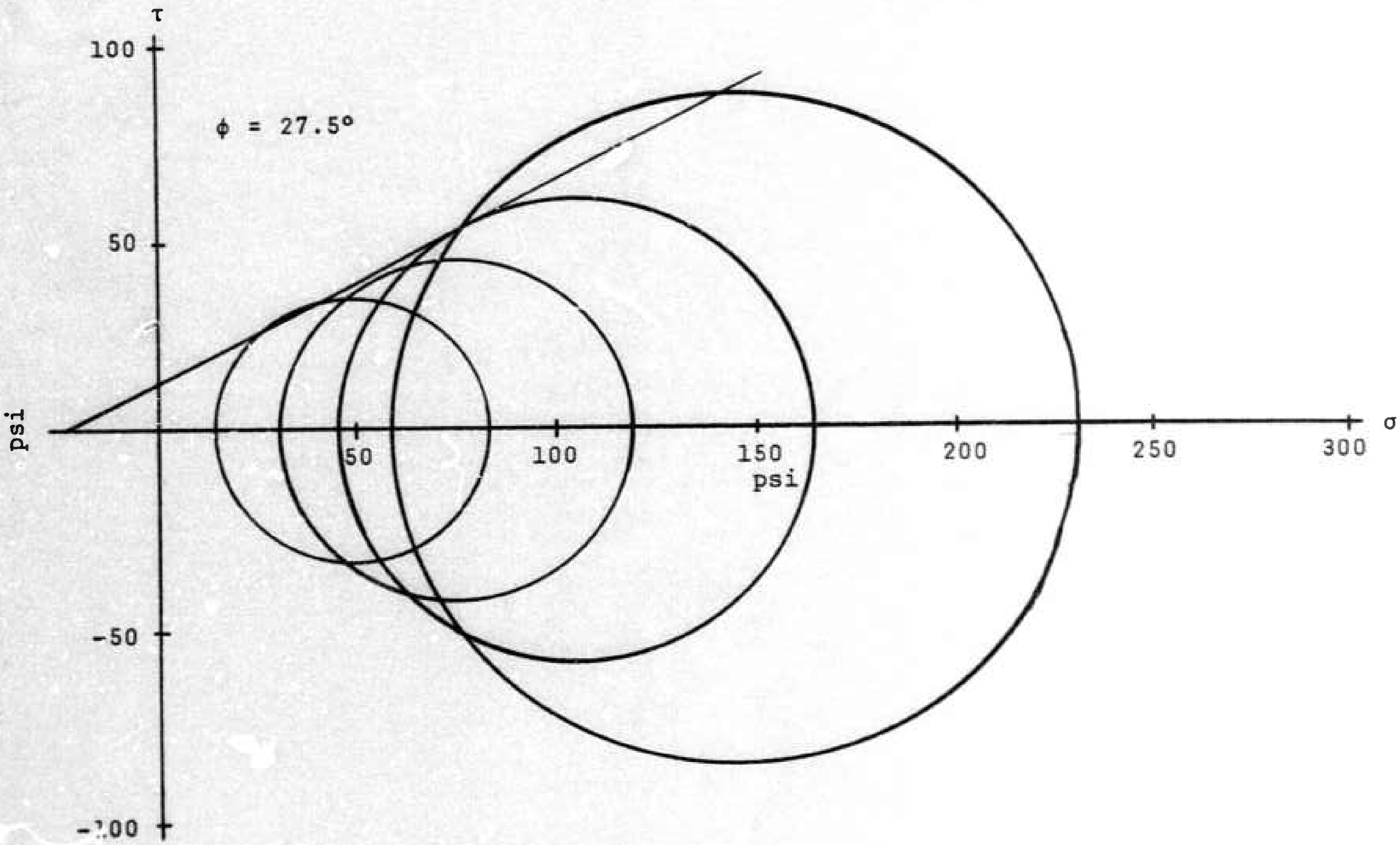

Figure 44. #6 Mesh Chicago (1.4 Inch Cell)

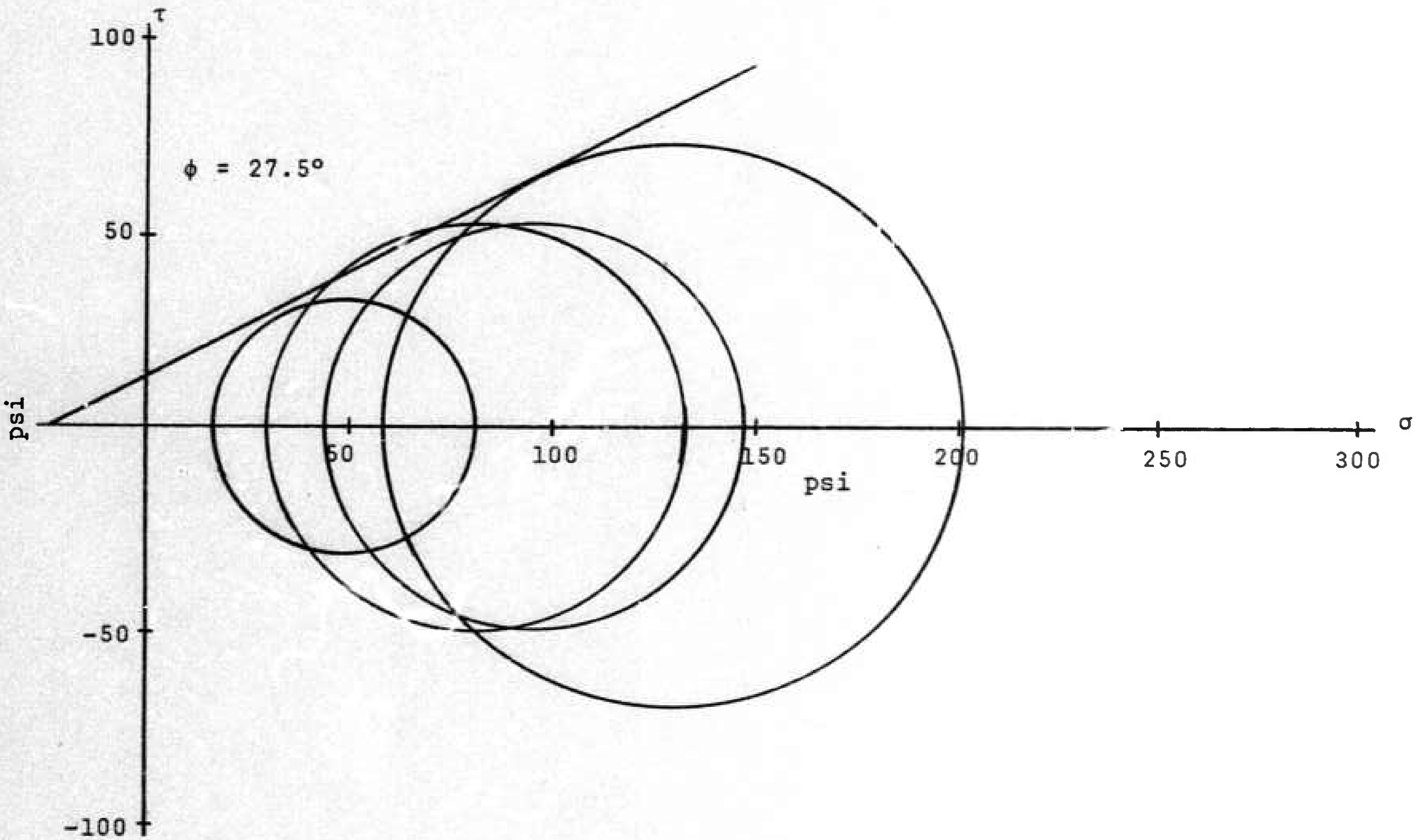

Figure 45. #6 Mesh Chicago (2.8 Inch Cell)

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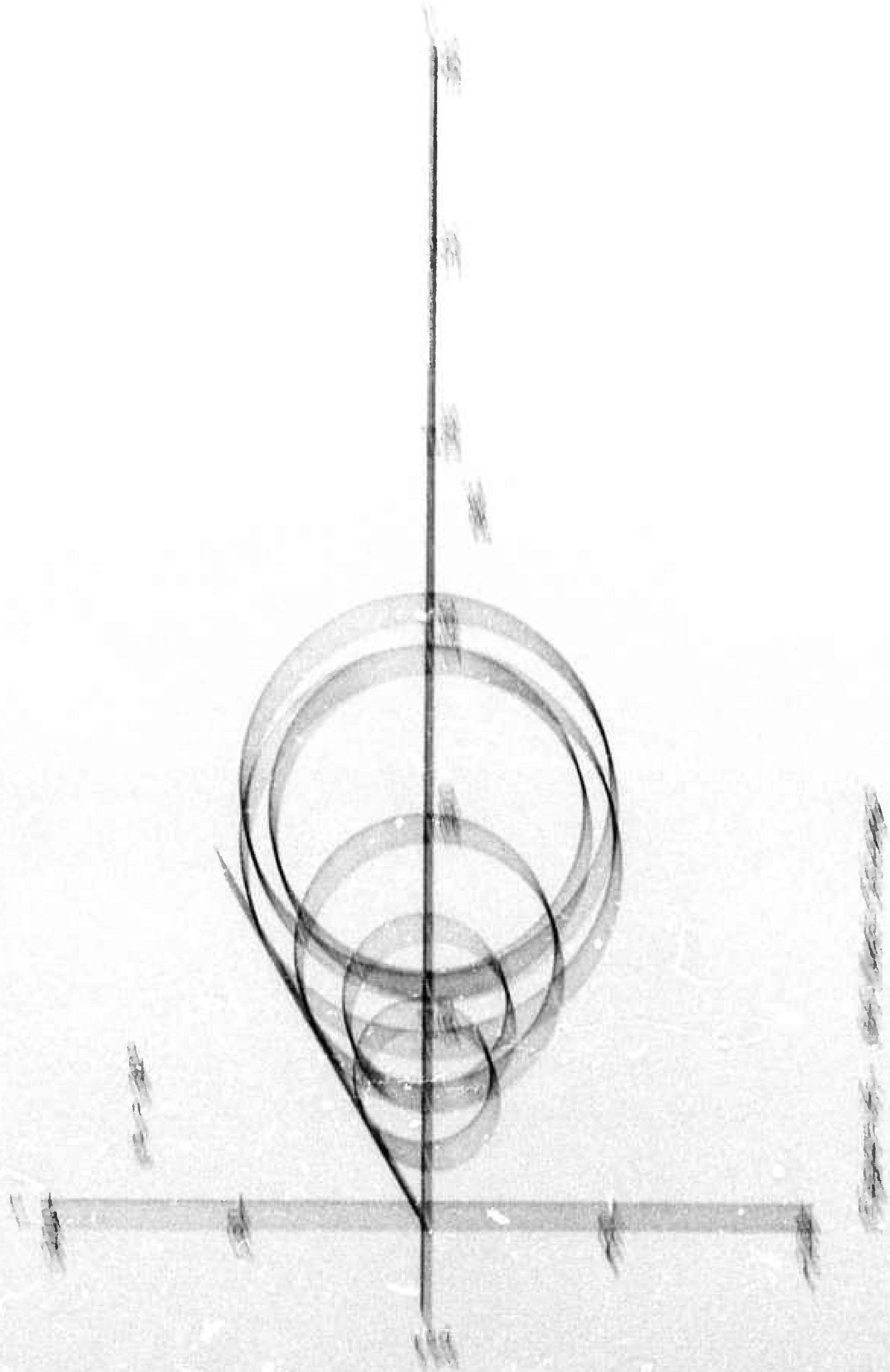

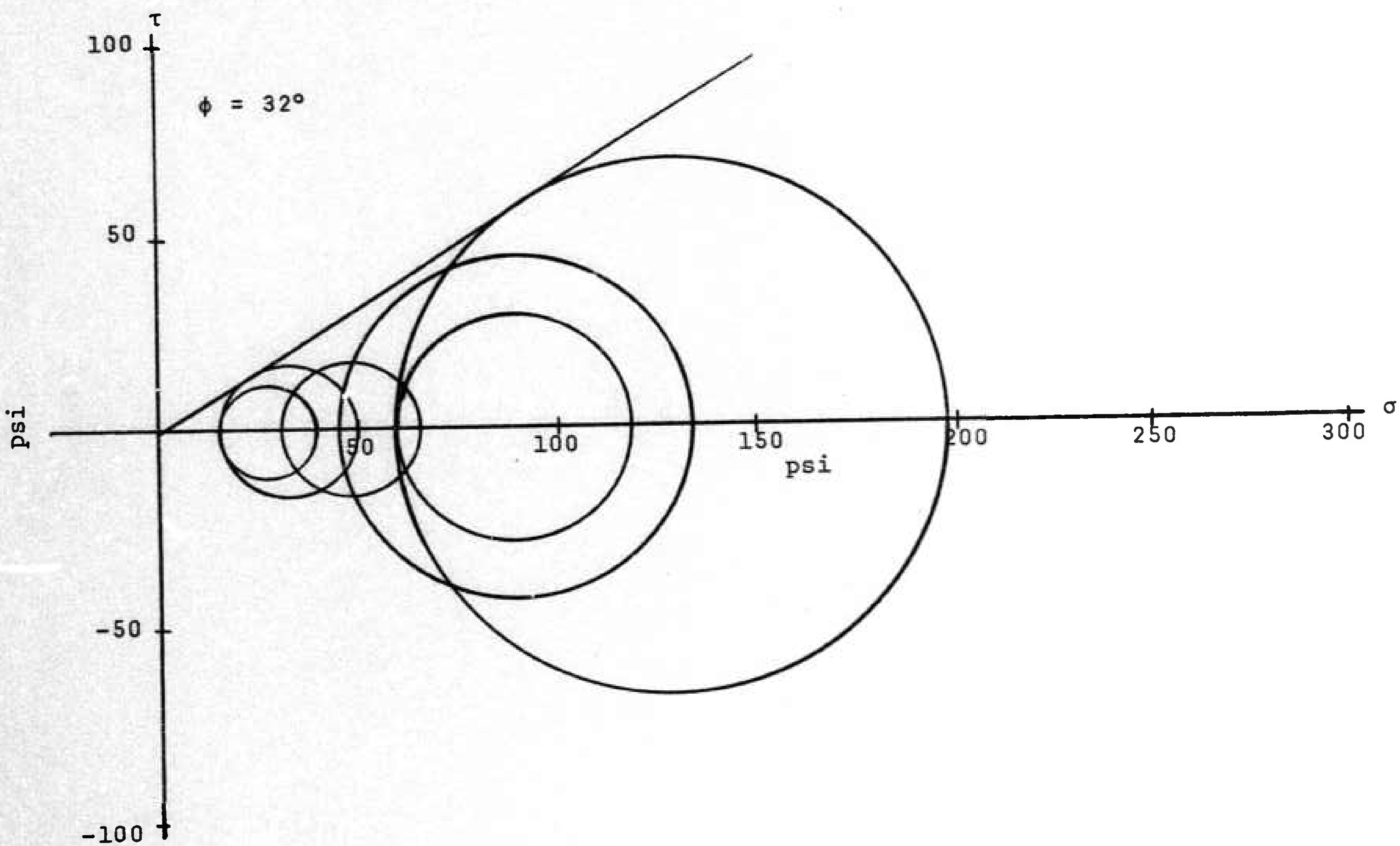

Figure 47. #140 Mesh Chicago

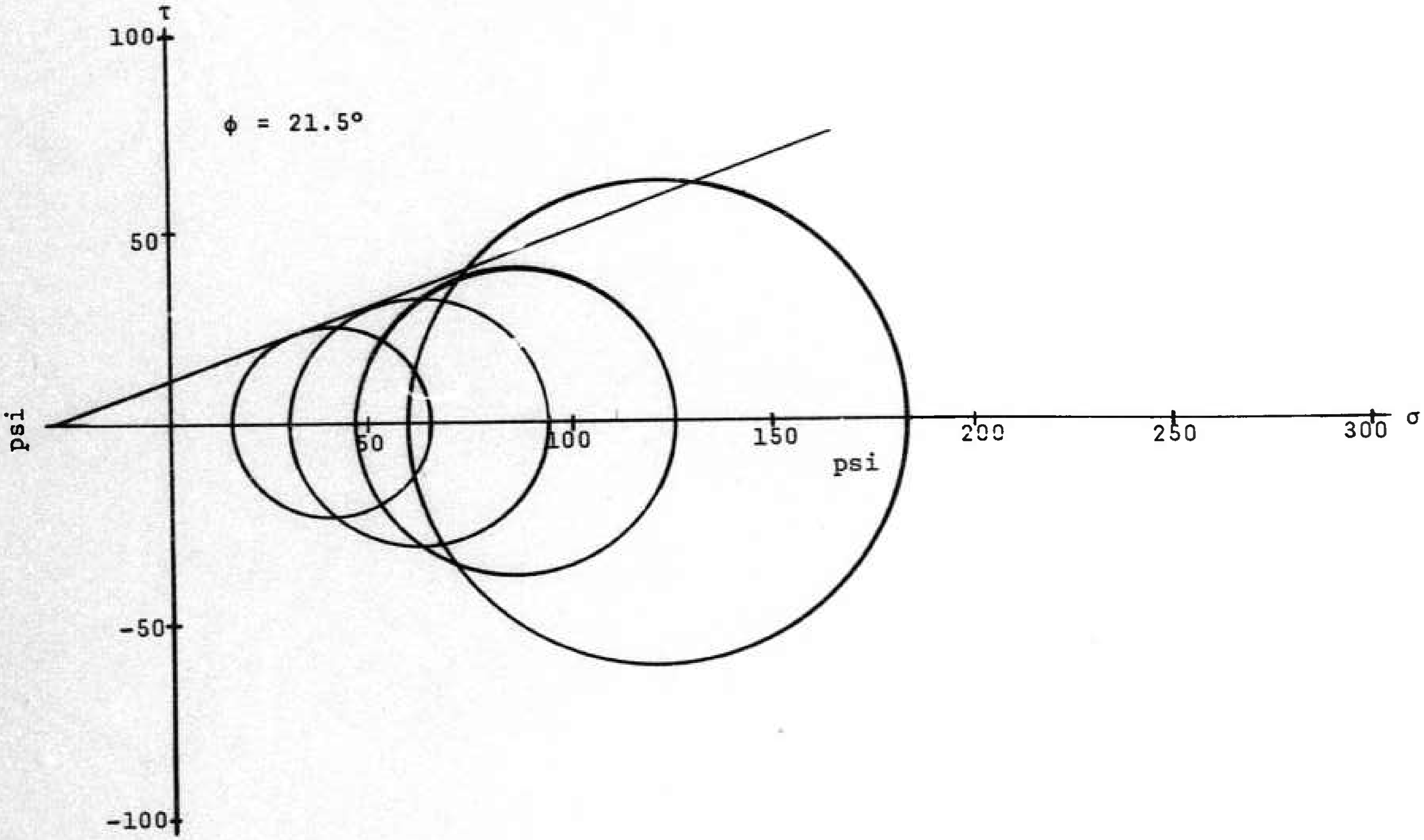

Figure 48. Combined Toronto

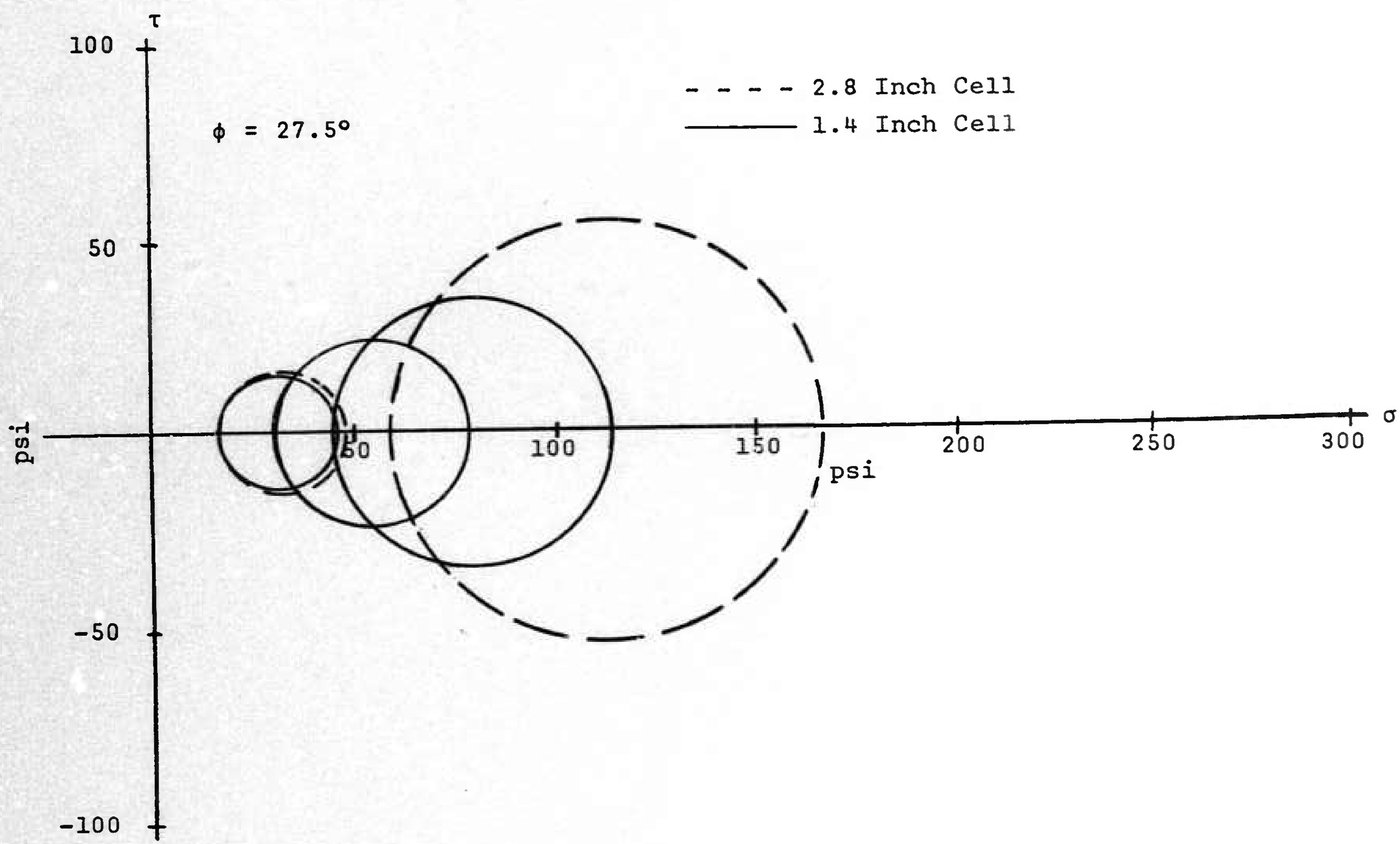

Figure 49. #6 Mesh Toronto

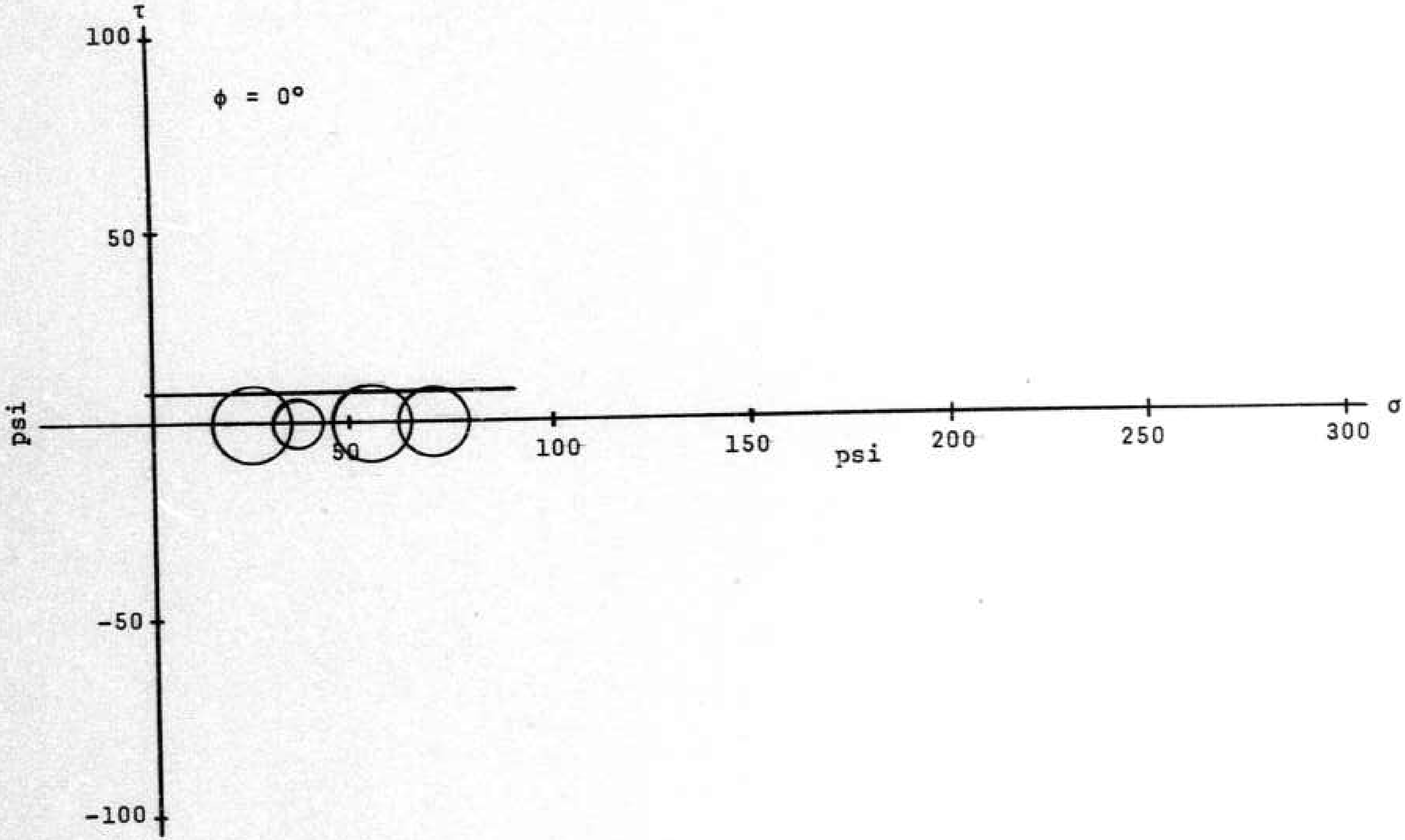

Figure 50. #40 Mesh Toronto

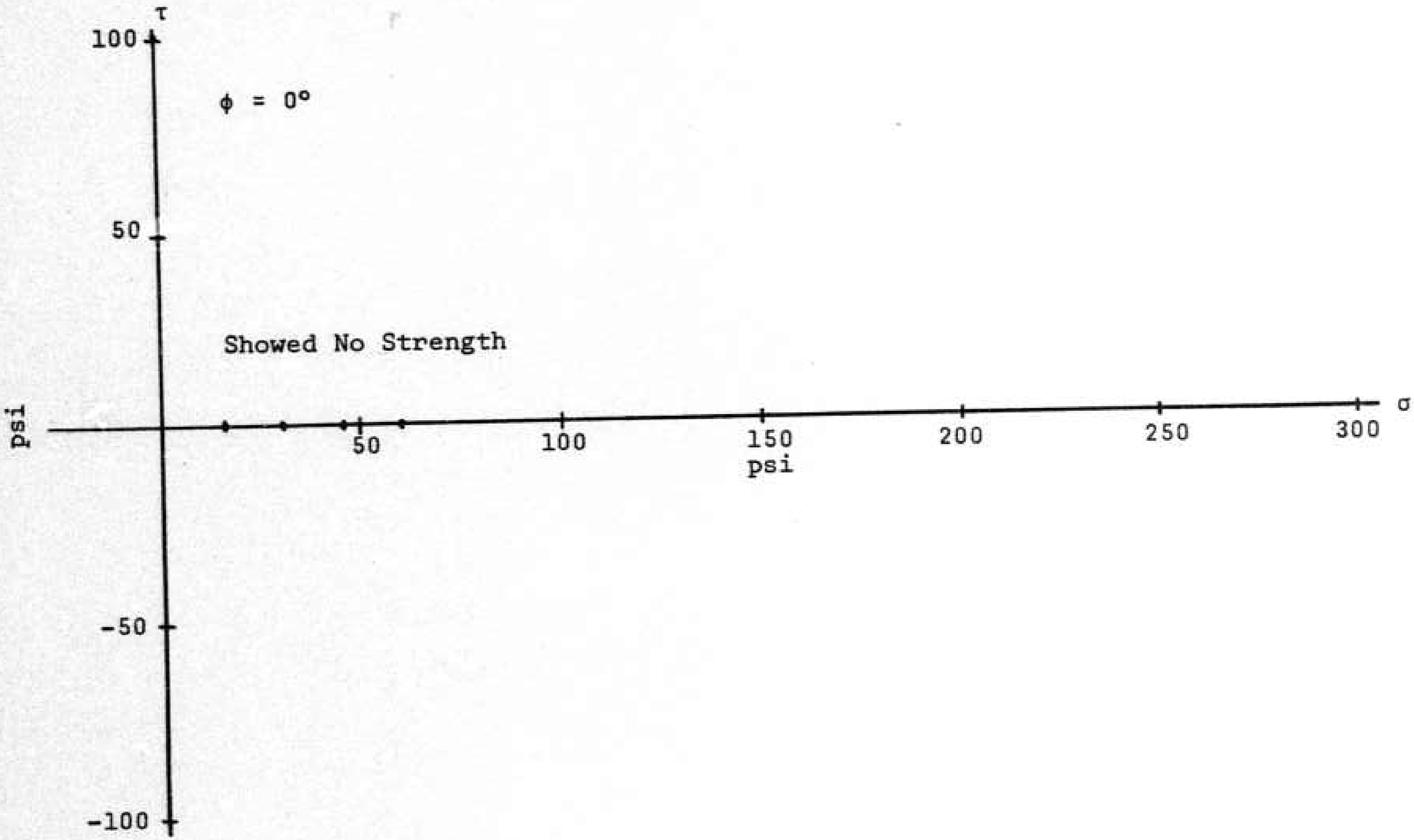

Figure 51. #140 Mesh Toronto

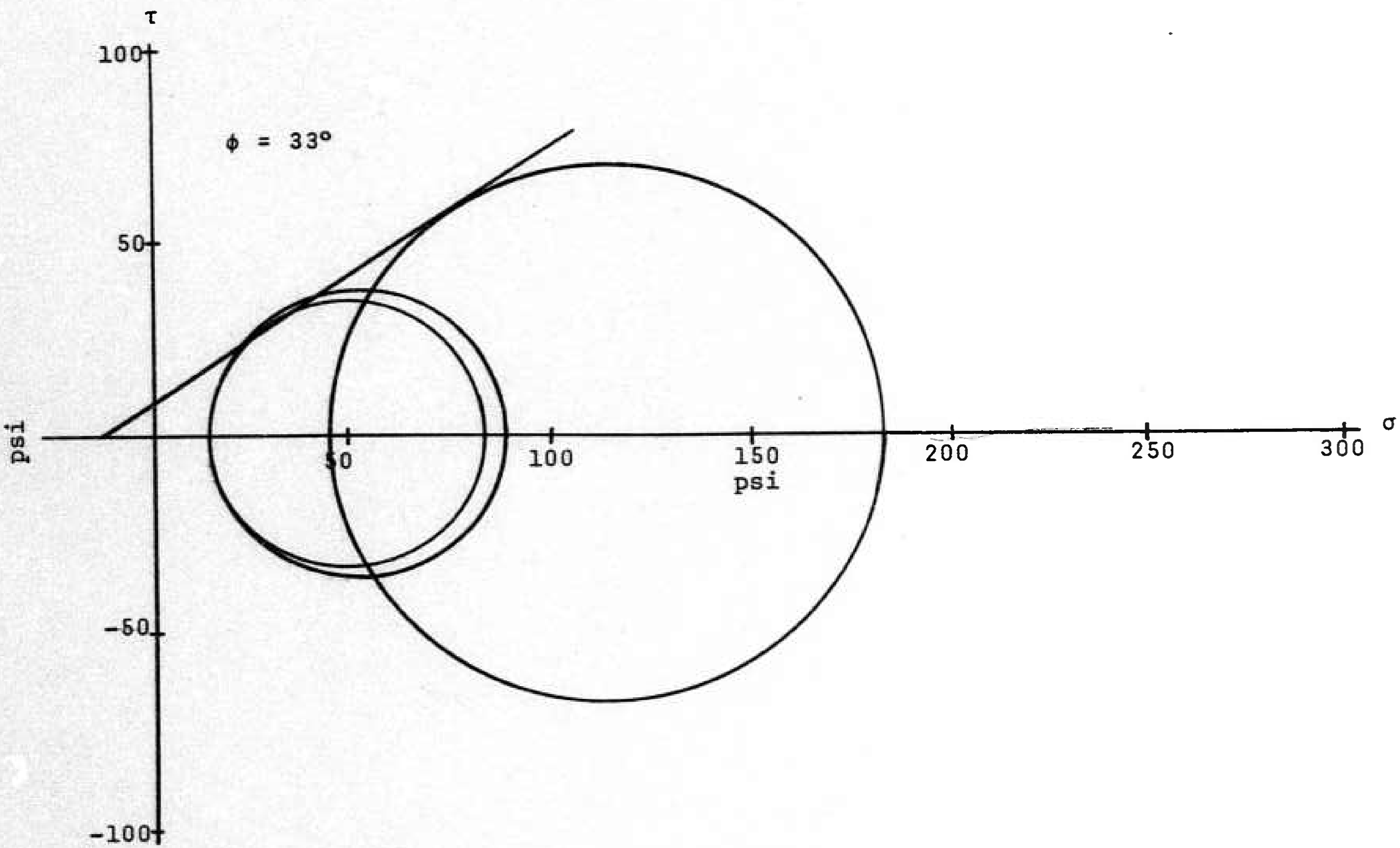

Figure 52. Combined White Pine Year I

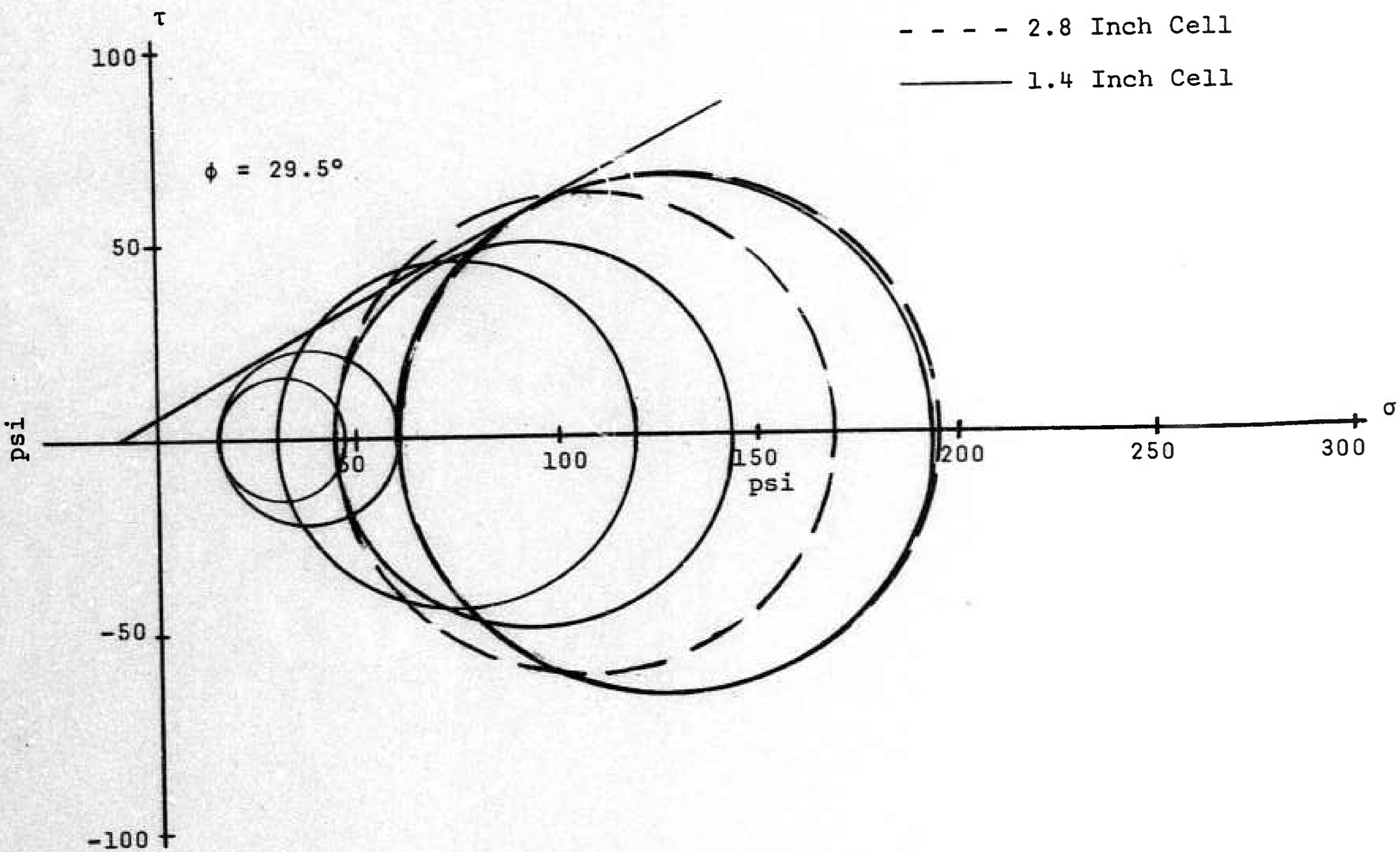

Figure 53. #6 Mesh White Pine

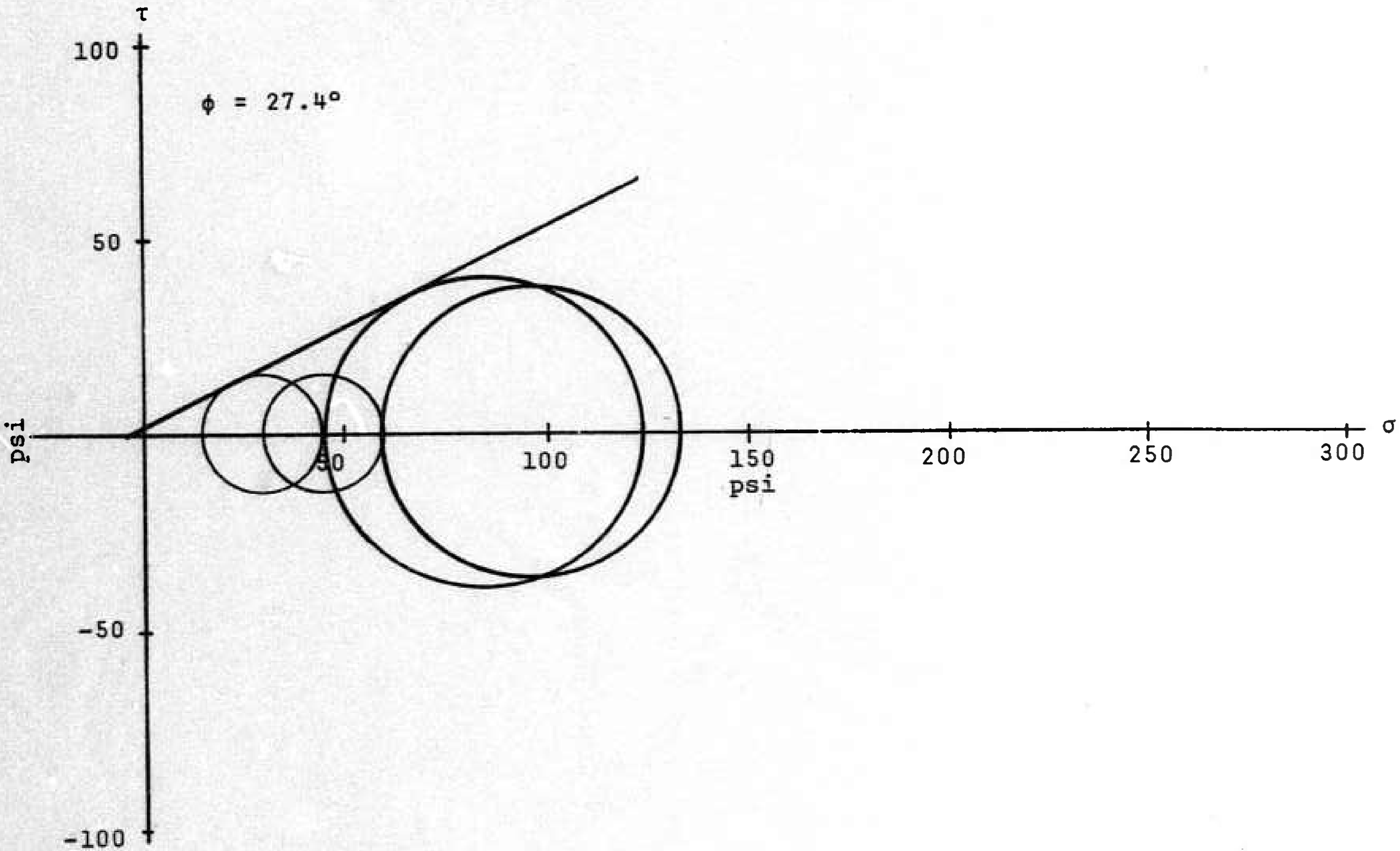

Figure 54. #40 Mesh White Pine

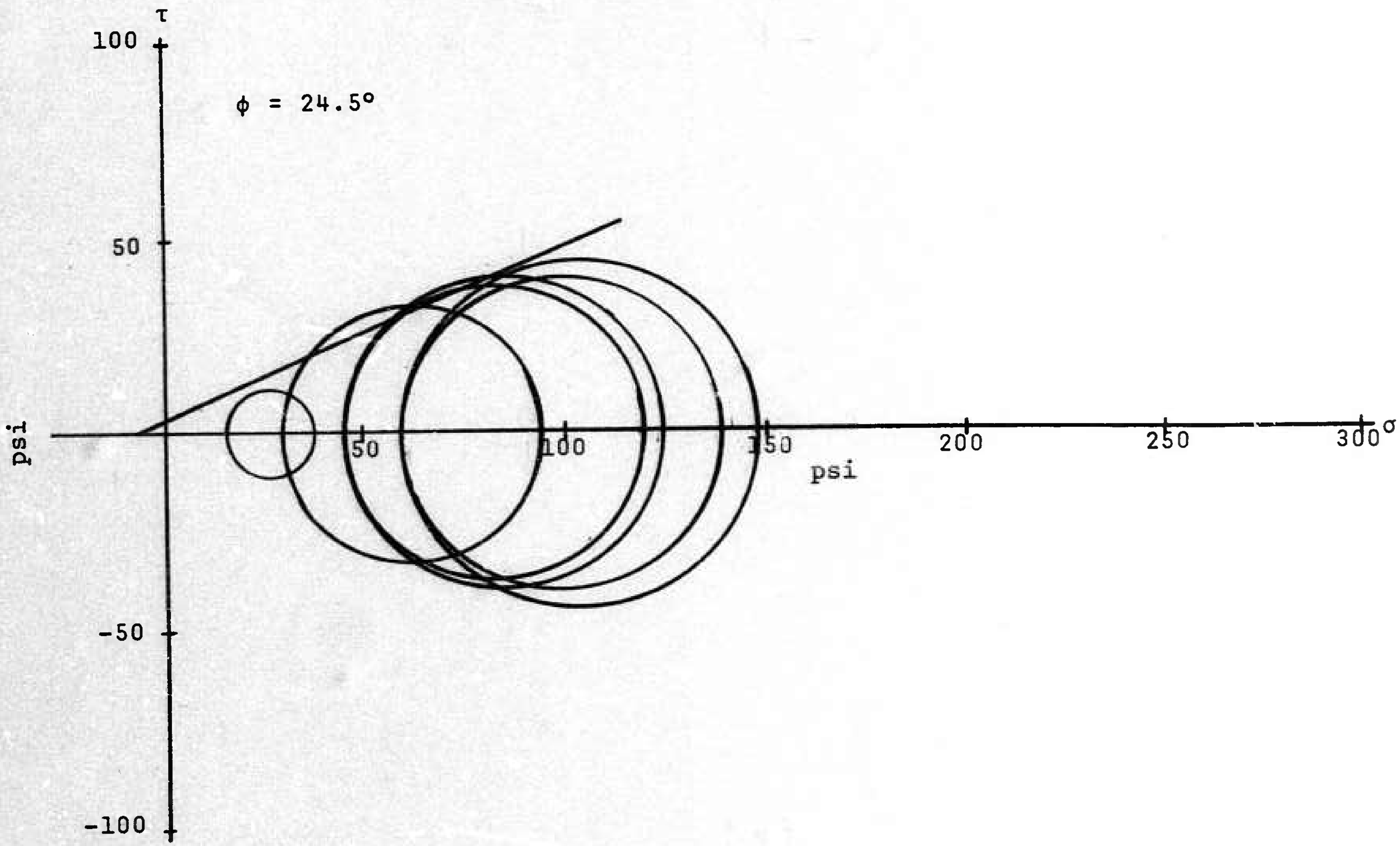

Figure 55. #140 Mesh White Pine

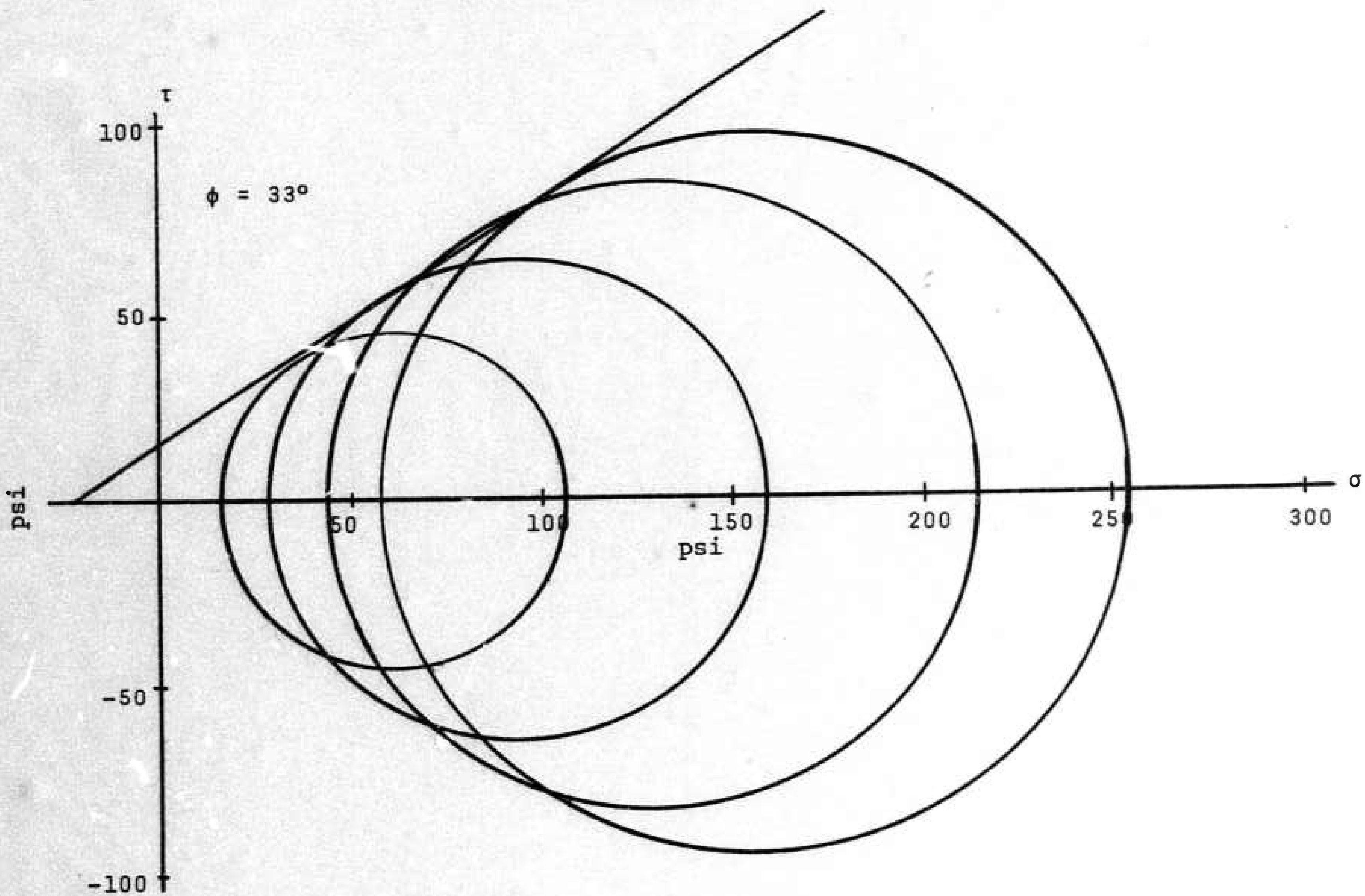

Figure 56. Combined White Pine Year II

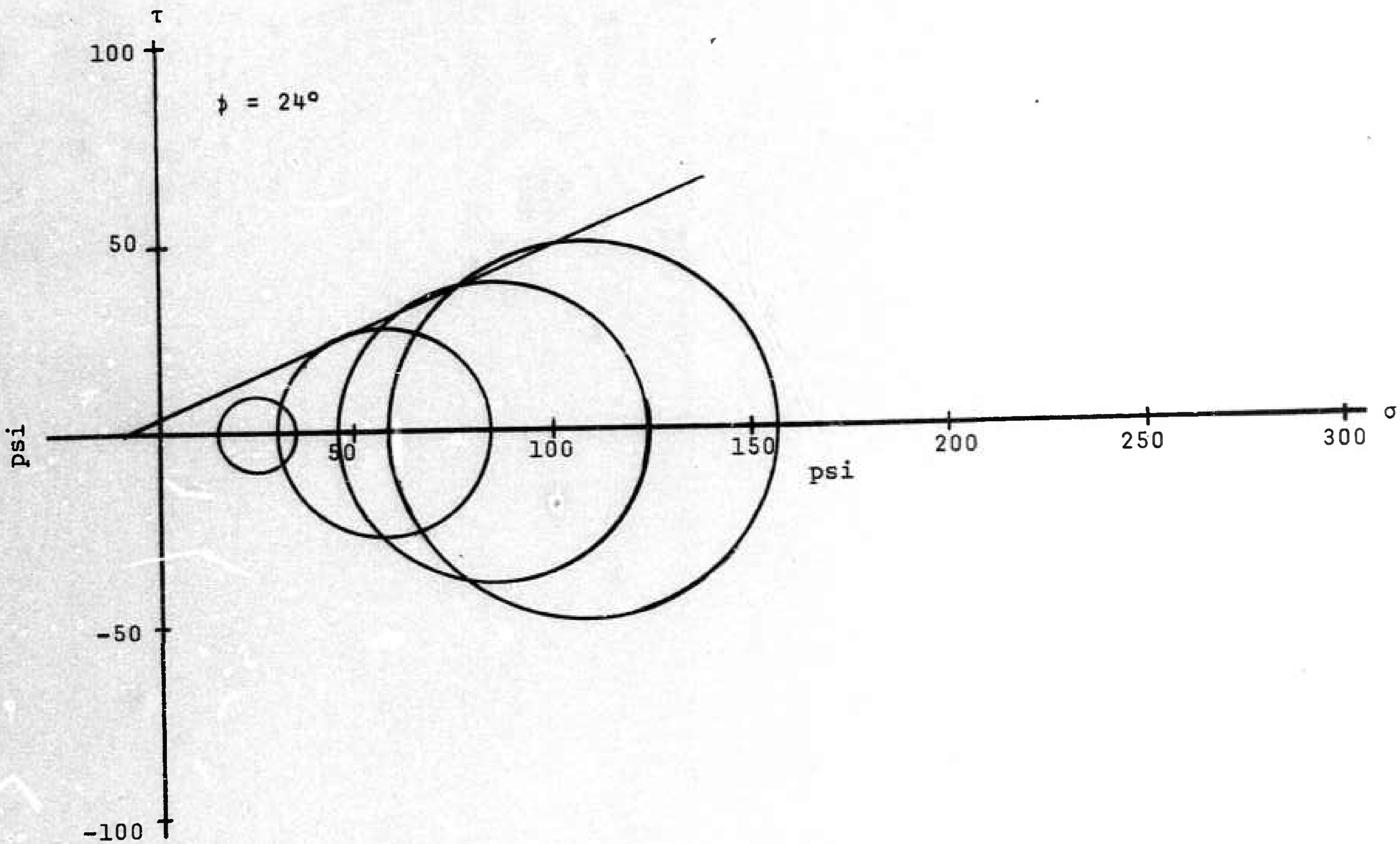

Figure 57. New York, Combined, Small

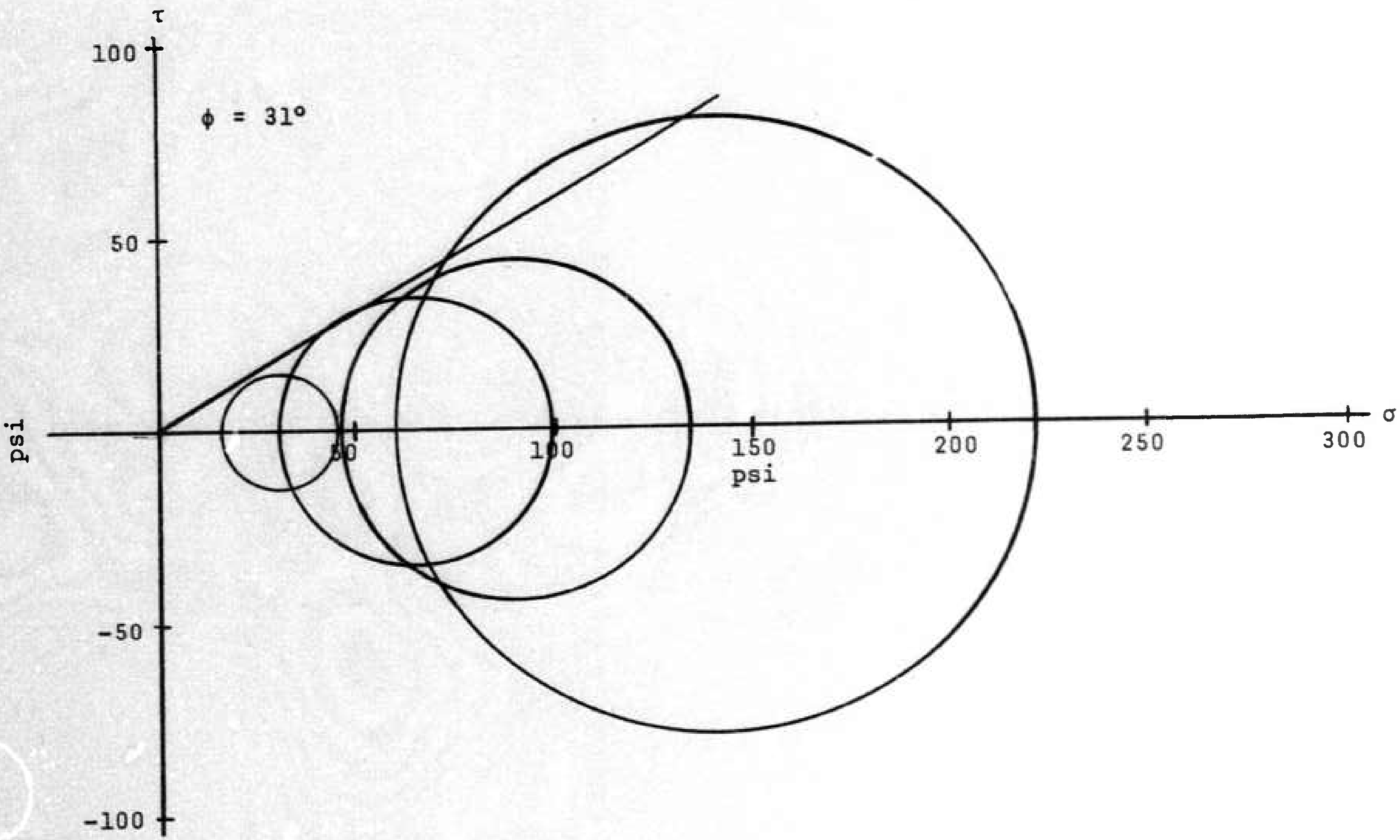

Figure 58. New York, Combined, Normal

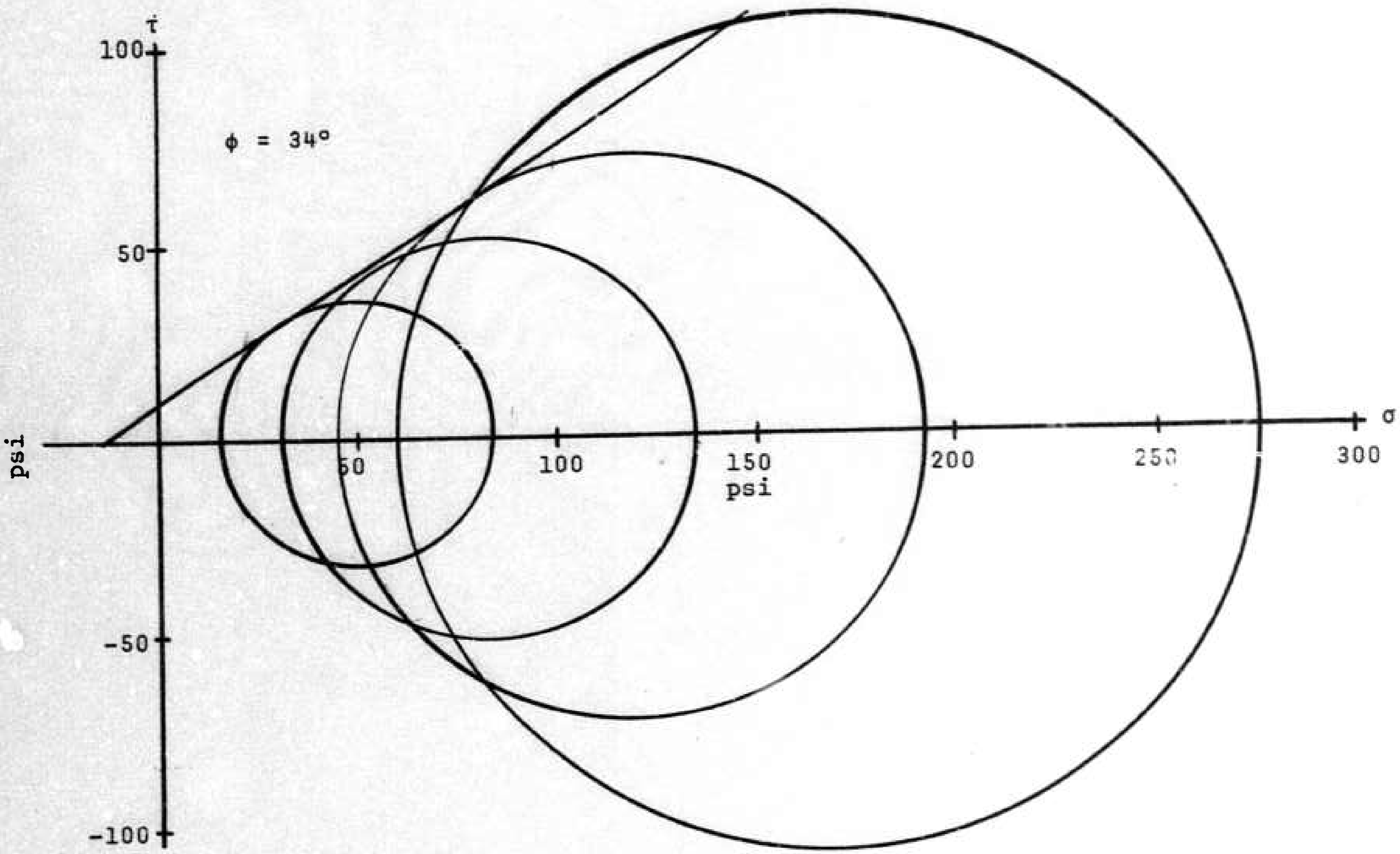

Figure 59. New York, Combined, Large

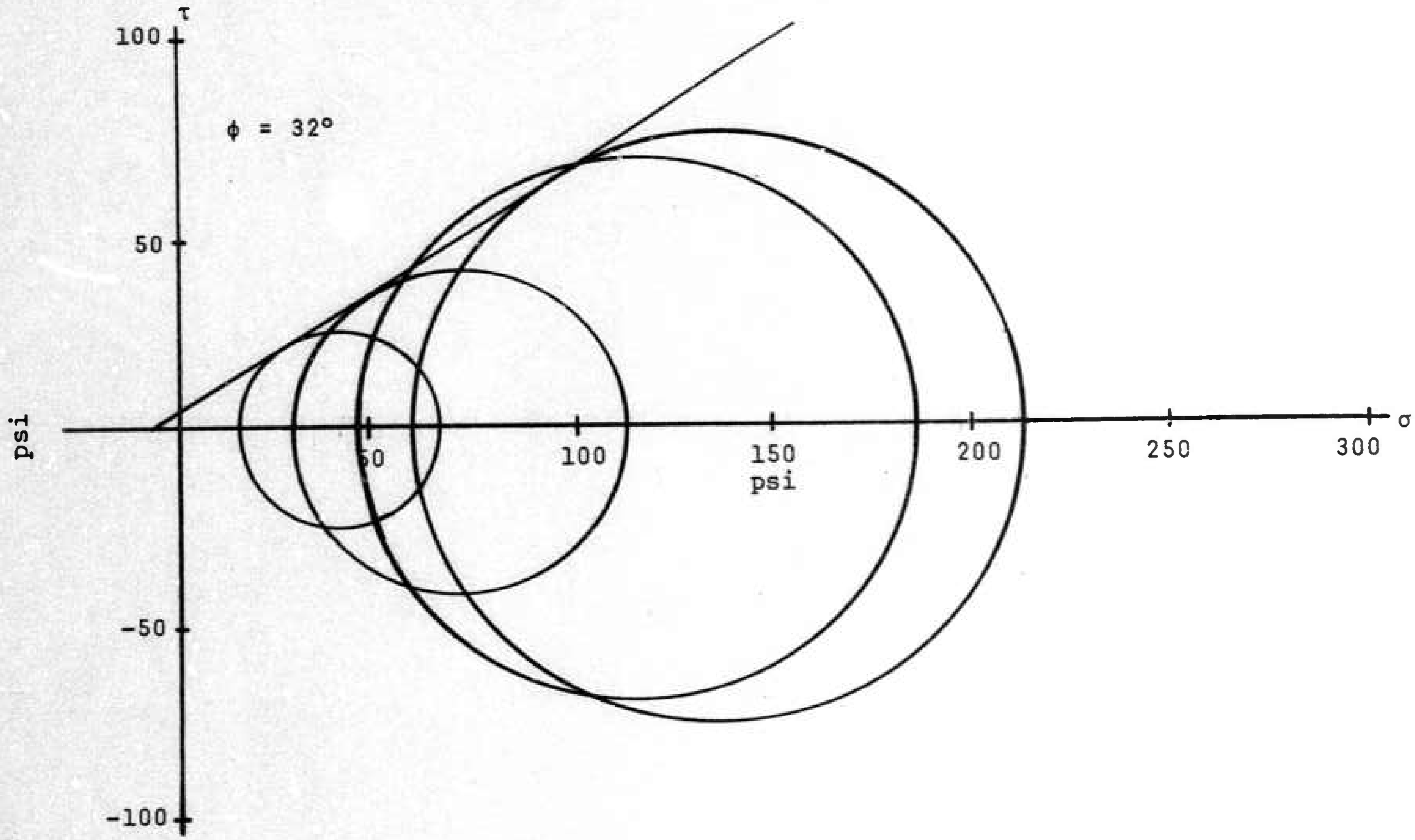

Figure 60. Cleveland, Combined, Dry

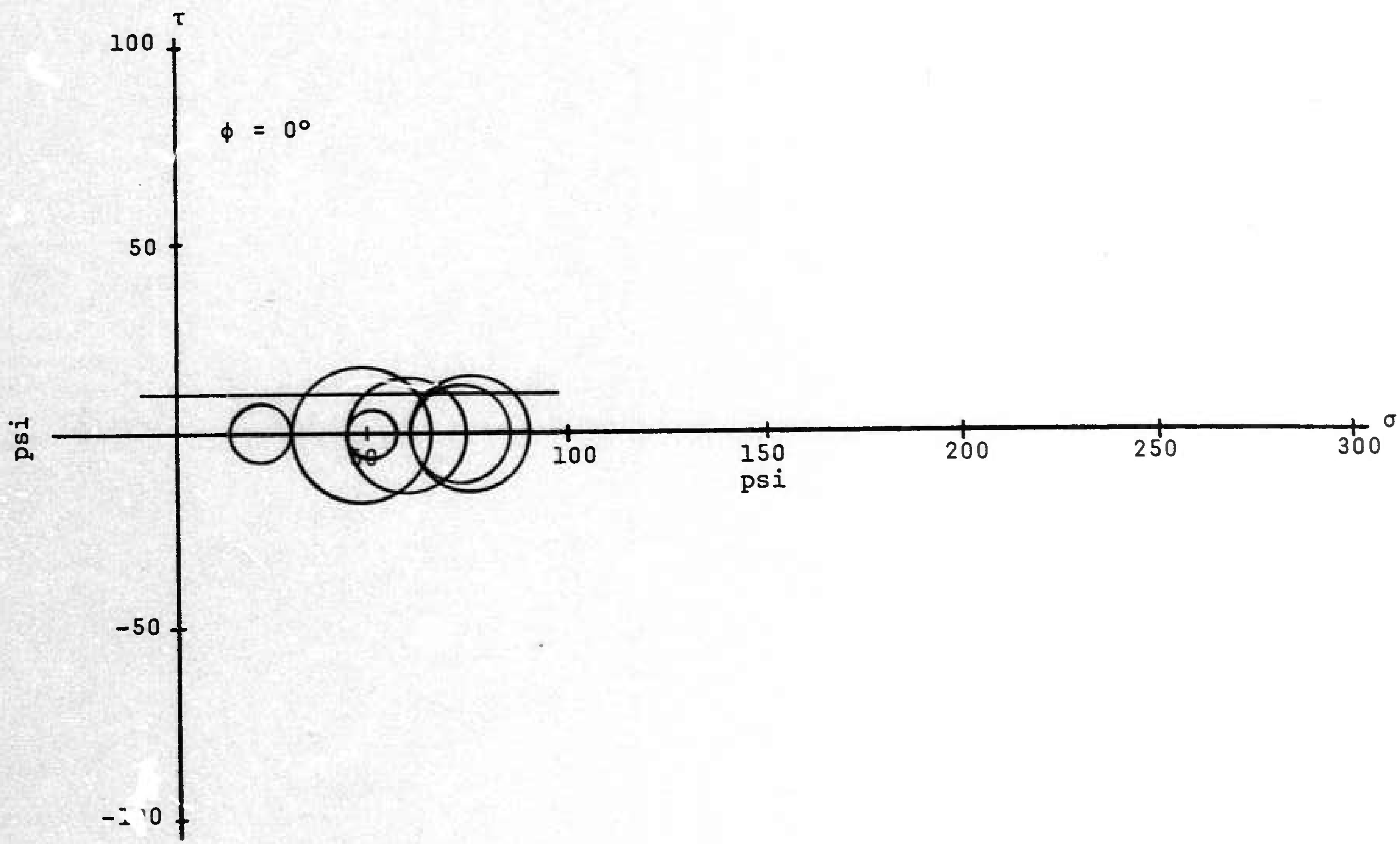

Figure 61. Cleveland, Combined, Water Saturated

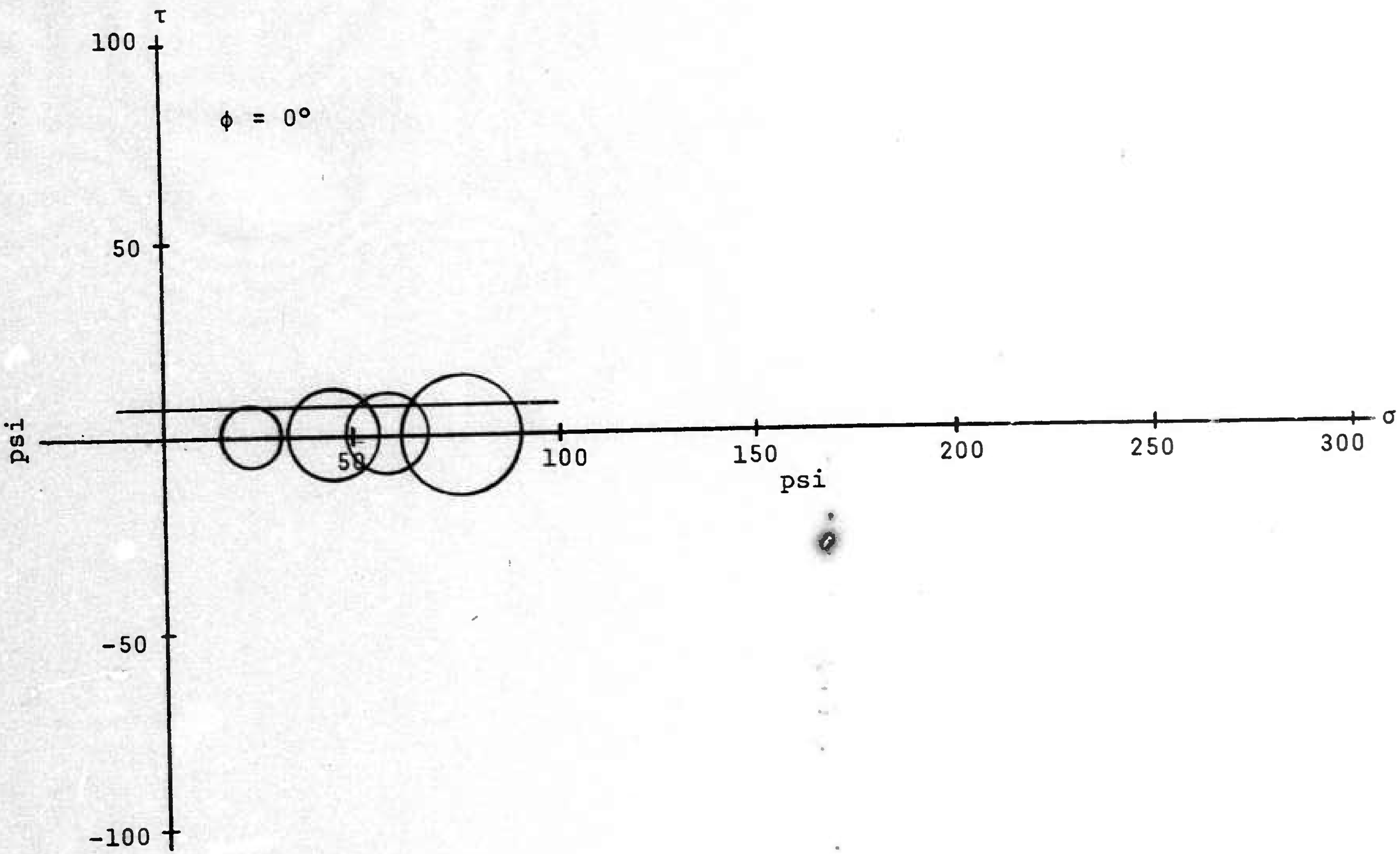

Figure 62. Cleveland, Combined, Detergent Saturated

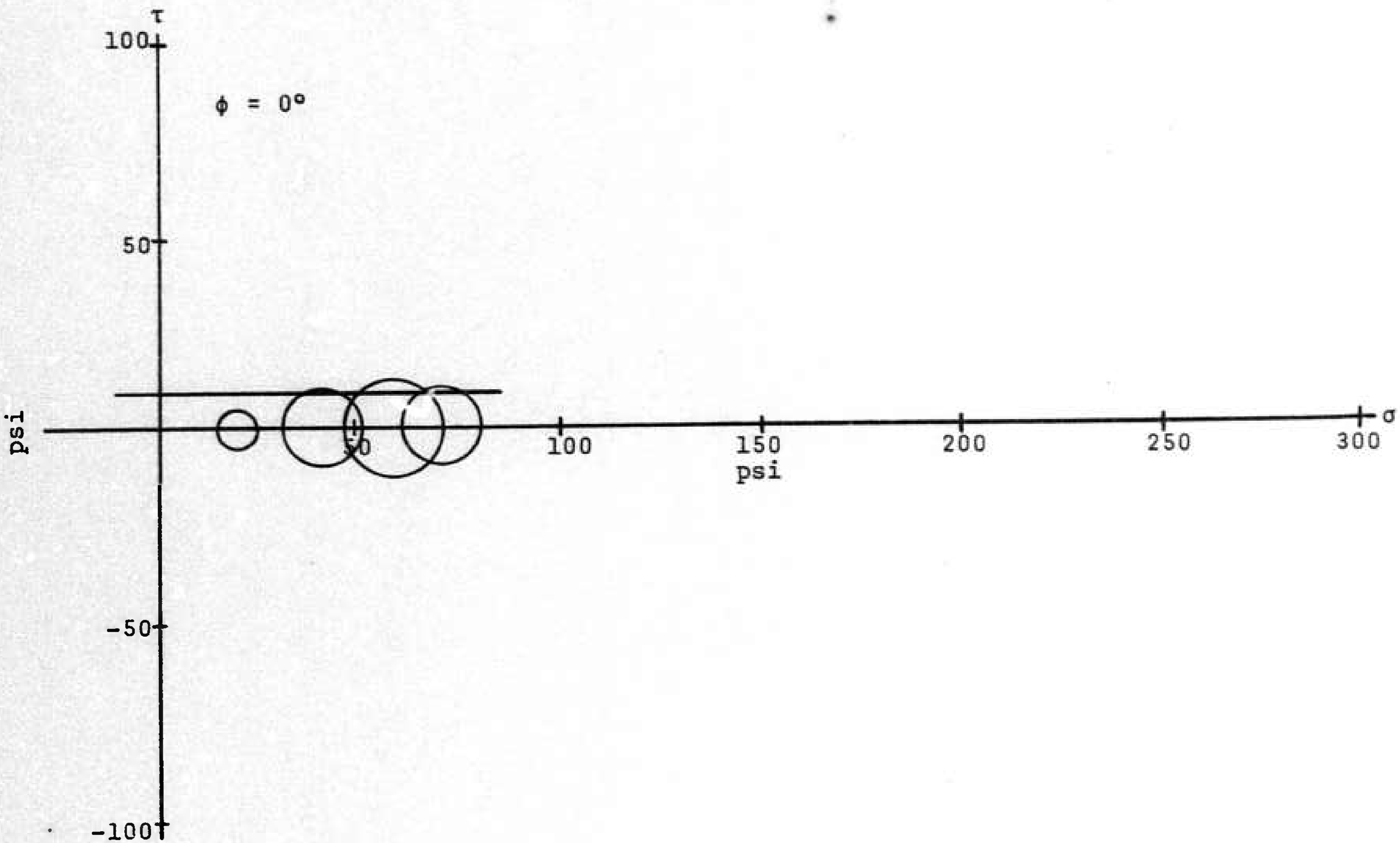

Figure 63. Cleveland, Combined, Sodium Citrate Saturated

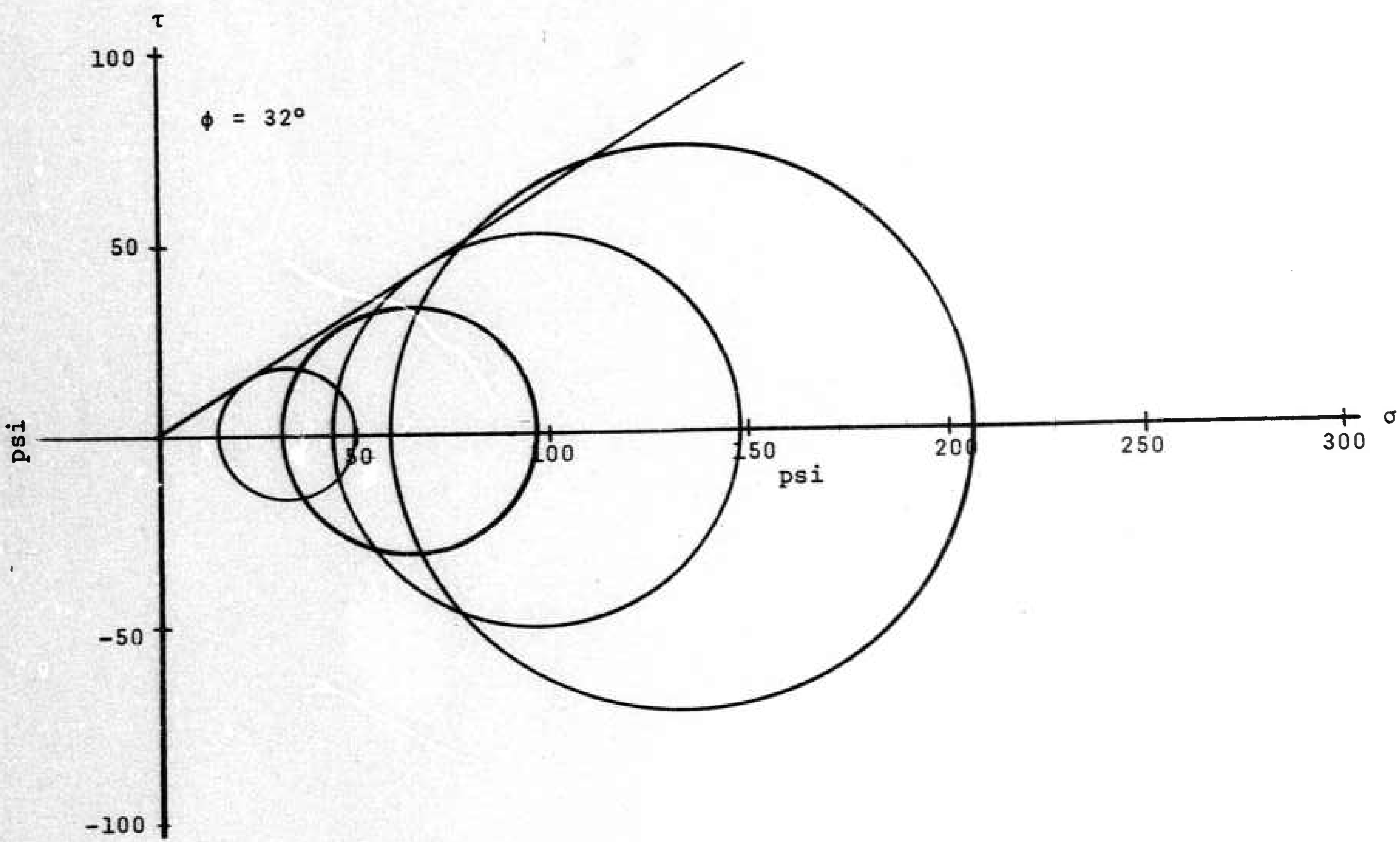

Figure 64. New York, Combined, Dry

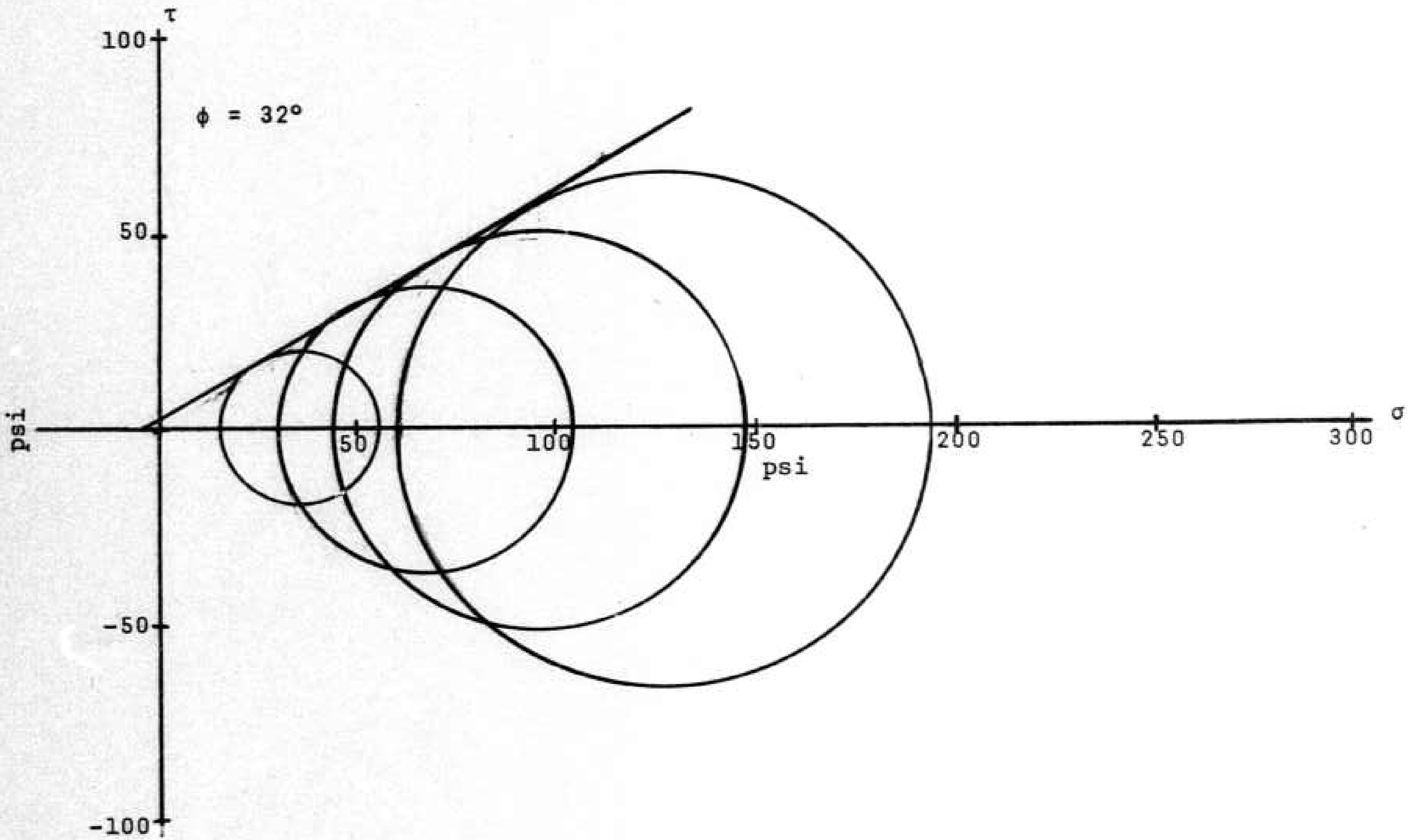

Figure 65. New York, Combined, Water Saturated

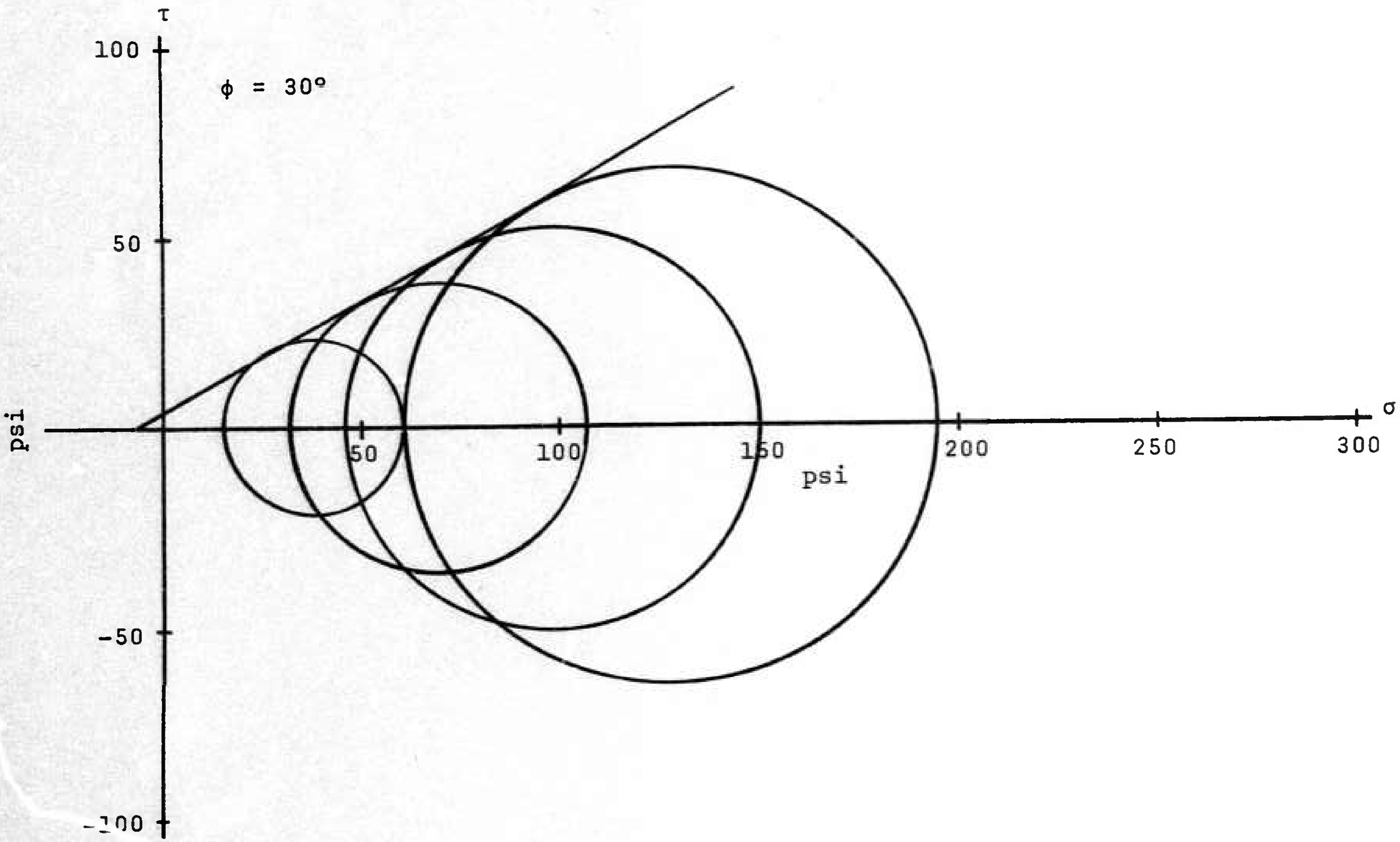

Figure 66. New York, Combined, Detergent Saturated

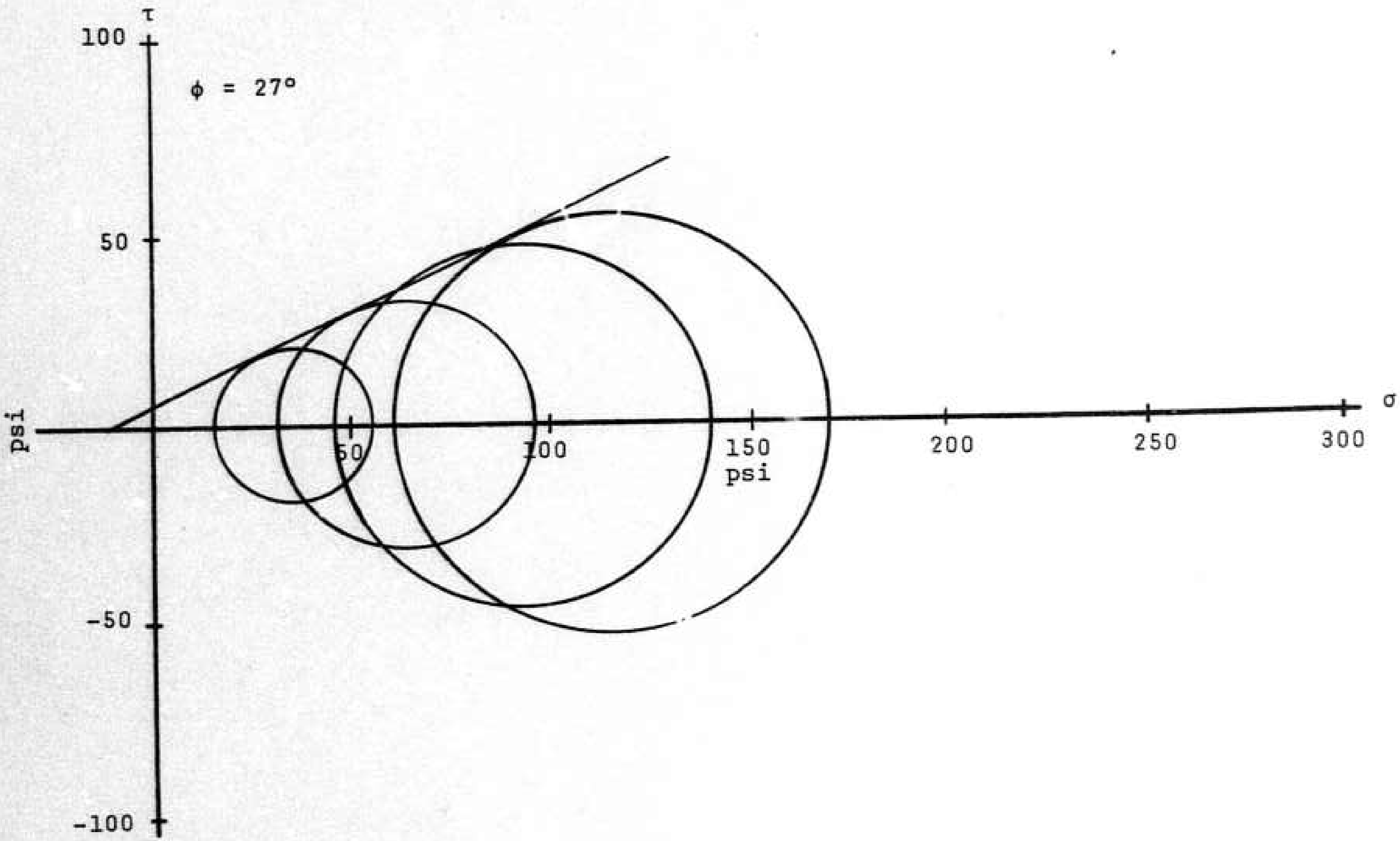

Figure 67. New York, Combined, Sodium Citrate Saturated

APPENDIX V

TABLES OF MOHR'S CIRCLE DATA

Table 17. Triaxial Stresses for Combined and Uniformly Graded Tests

Location	Phila-delphia		Farming-ton('71)		Heber City		Toronto		White Pine('71)		Nast		Chicago	
Particle Size	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
Combined	20	78	20	63	20	32	15	66	15	83	15	54	15	82
	20	72	40	122	40	49	30	95	15	91	30	78	30	145
	40	137	60	182	60	108	45	138	45	136	30	118	45	185
	40	123	70	161	70	77	60	183			45	170	60	270
	60	191	70	156							60	238		
	60	176												
	70	211												
	70	210												
6 Mesh	20	75					15	45	15	48	15	86	15	85
	40	133					15*	49	15*	60	30	125	15*	82
	60	160					30	78	30	120	45	154	30	120
	70	218					45	115	45	145	60	208	30*	135
							60*	169	45*	170			45	166
									60	195			45*	149
									60*	197			60	232
													60*	205

Table 17 (Continued)

Location	Phila-delphia		Farming-ton('71)		Heber City		Toronto		White Pine('71)		Nast		Chicago	
Particle Size	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
40 Mesh	20	78	20	114	20	32	15	35	15	45	15	85	15	52
	40	121	20	75	40	62	30	42	30	60	30	135	30	75
	40	144	40	195	60	82	45	65	45	125	45	130	30	102
	60	206	40	251	70	90	60	80	60	135	45	168	45	145
	60	204	40	108							60	158	60	144
	70	202	60	280							60	165	60	158
	70	251	60	165										
			65	233										
			70	291										
140 Mesh	20	72	20	56	20	31	15	15	15	40	15	60	15	39
	40	141	20	55	40	58	30	30	30	96	30	96	15	49
	60	214	40	114	60	60	45	45	45	121	45	145	30	66
	70	249	40	85	70	85	60	60	45	126	60	205	45	133
			60	214					60	141			60	121
			60	134					60	149			60	200
			65	142										
			70	223										

*2.8-inch cell.

Table 19. Triaxial Stresses for Gradation Variations Tests

New York					
Small		Normal		Large	
σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
15	36	15	47	15	83
30	83	30	101	30	137
45	125	45	134	45	191
60	157	60	223	60	305

Table 20. Triaxial Stress for Some Miscellaneous Tests

Heber City 12 mesh		Farmington 20 mesh		White Pine Combined('72)	
σ_1	σ_3	σ_1	σ_3	σ_1	σ_3
20	62	20	58	15	109
40	109	40	110	30	160
60	136	60	195	45	215
70	174	65	175	60	253
		65	197		